

Neuroscience to Applications

Computational Neuroscience at
Sandia National Laboratories

Brad Aimone

Neuroscience

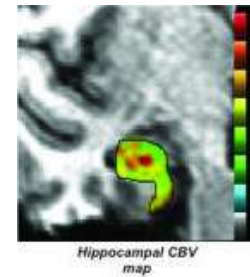
Molecular



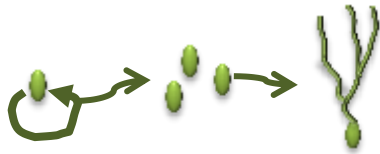
Electro-physiology



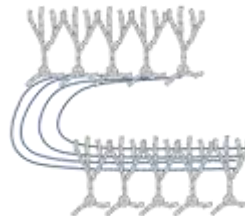
Cognitive



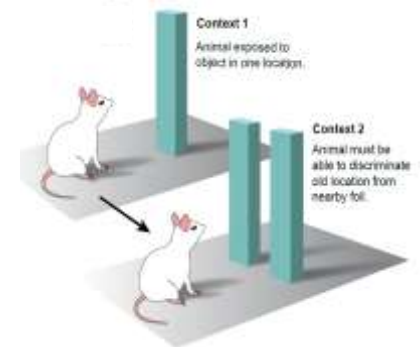
Developmental



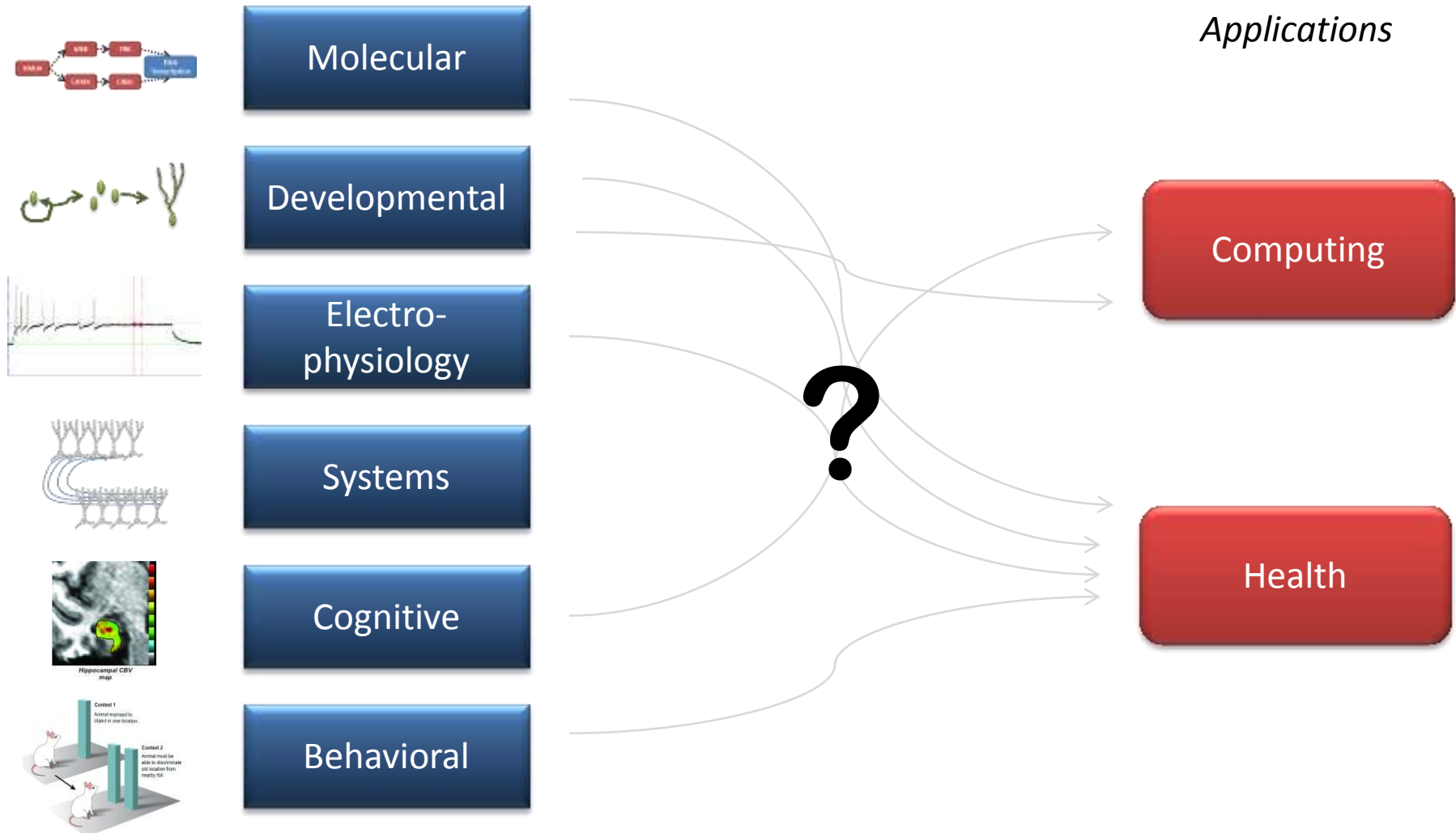
Systems



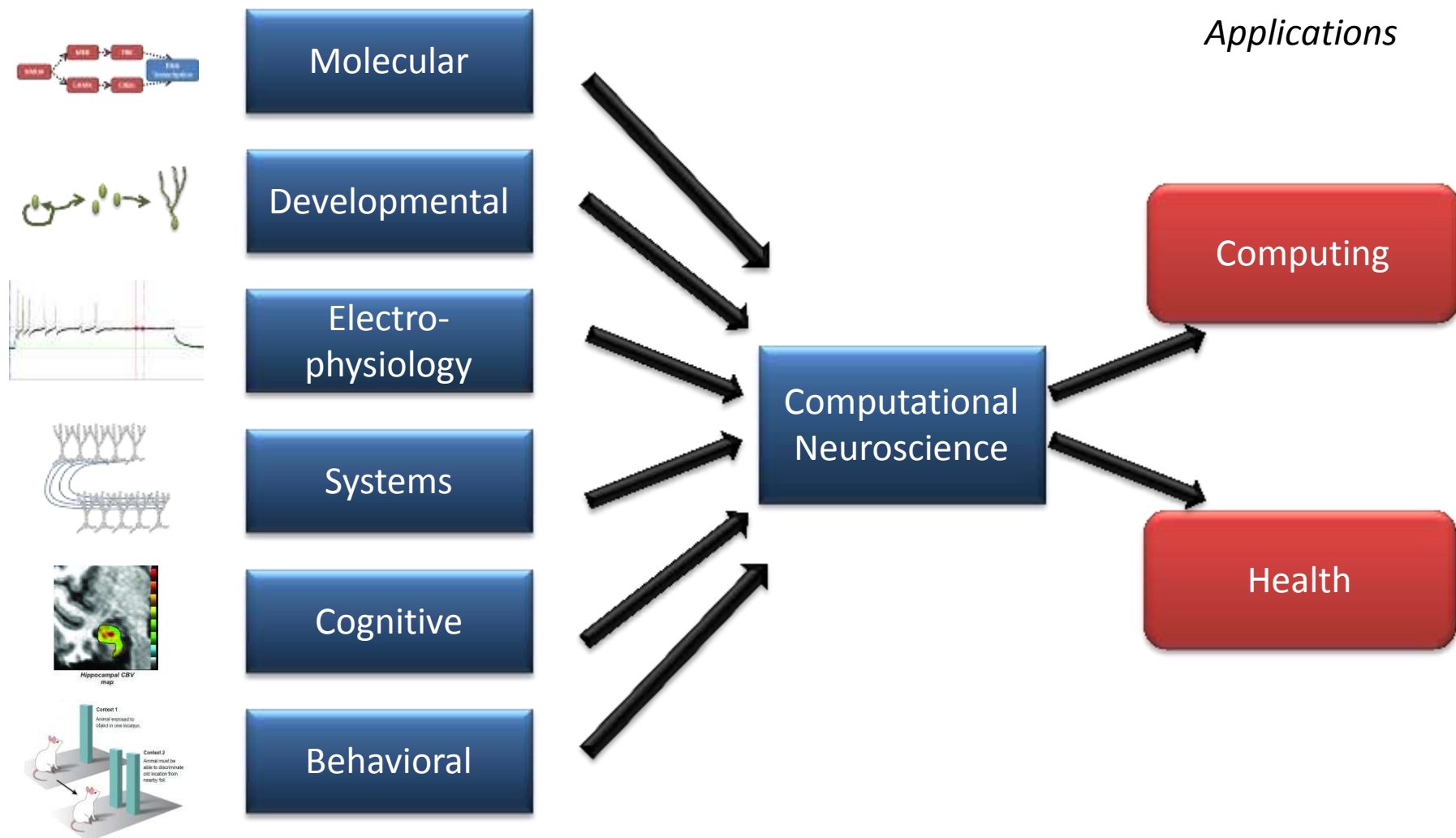
Behavioral



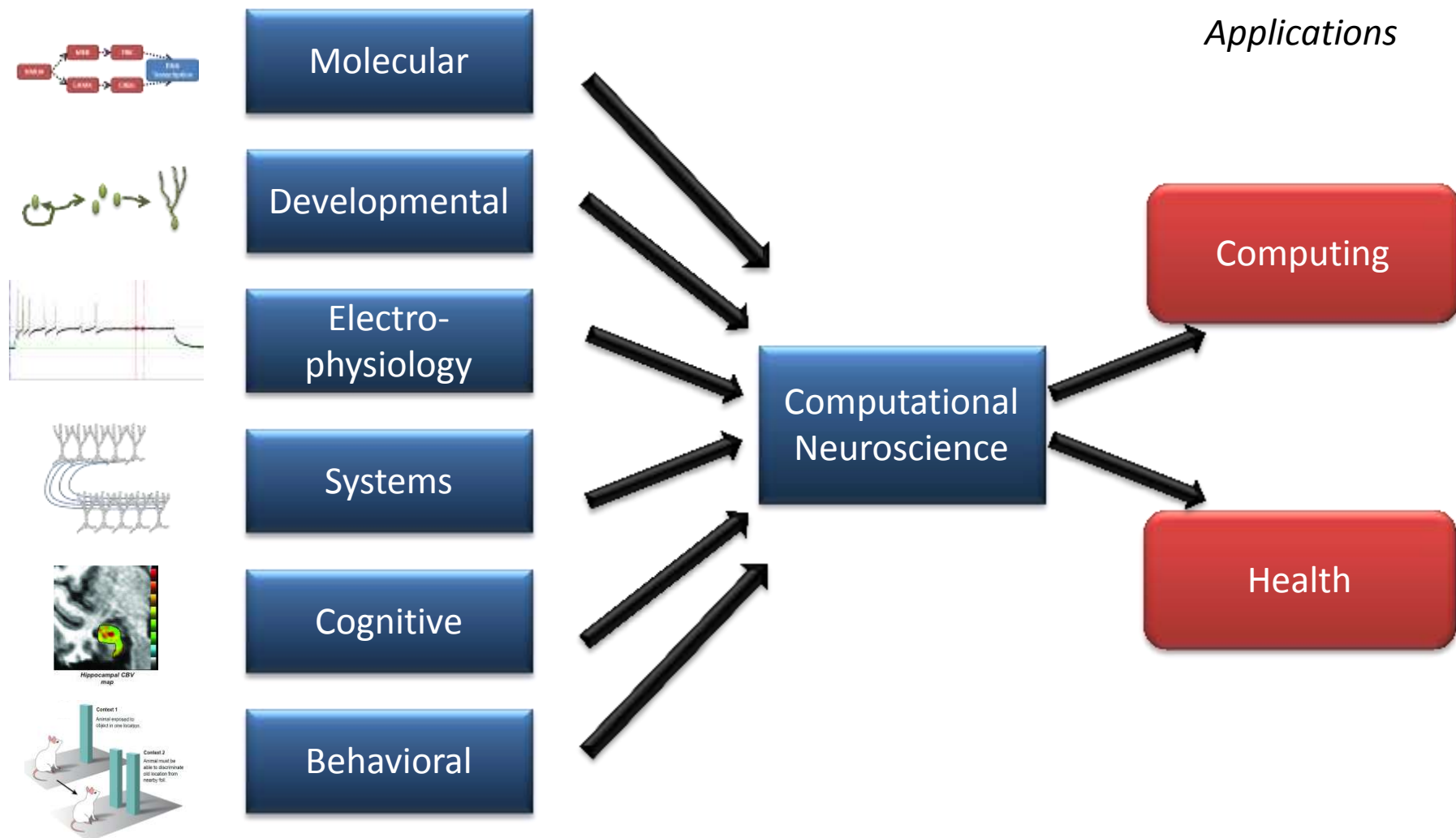
Neuroscience to Applications



Neuroscience to Applications

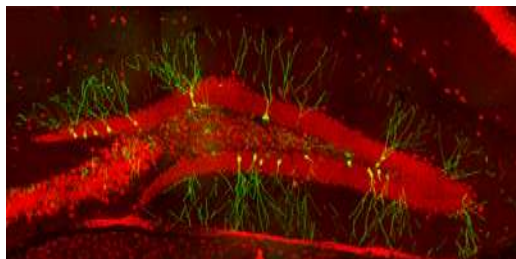


Neuroscience to Applications



Neuroscience at Sandia

- Computational Neuroscience



Adult Neurogenesis

- Simulation Design Platform



Neurons to Algorithms

- Simulation Engine and Analysis



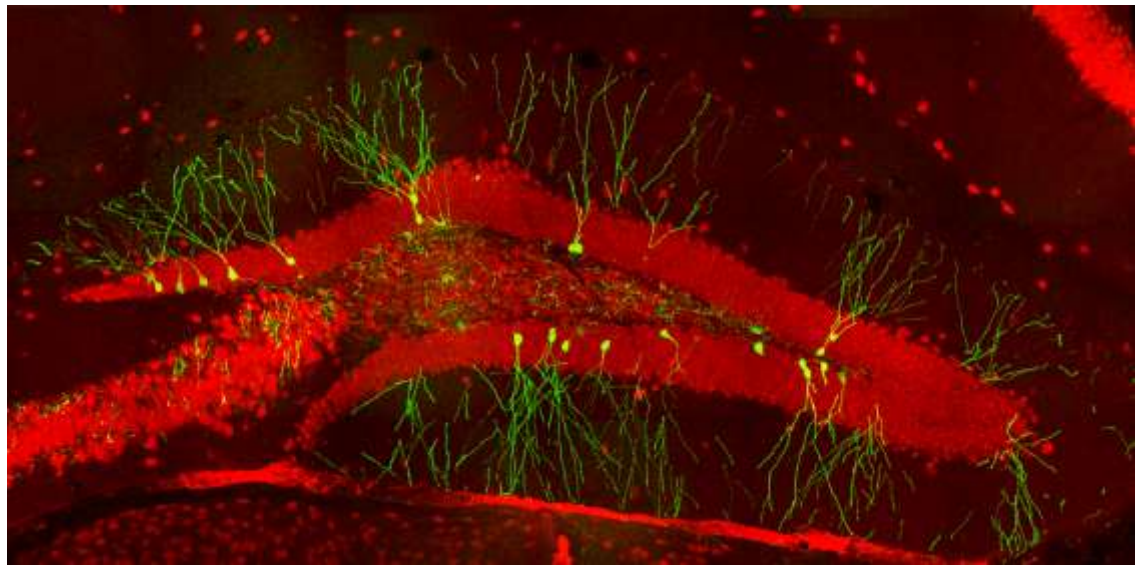
Stretching from data to a useful model

Case study: adult neurogenesis

- Biologically very well characterized at low levels
- Big questions
 - Relevance in humans
 - What types of cognition would it affect?
- Substantial application impact
 - Target for in psychiatric and neurological therapeutics
 - Novel form of algorithm – plasticity at neural scales?

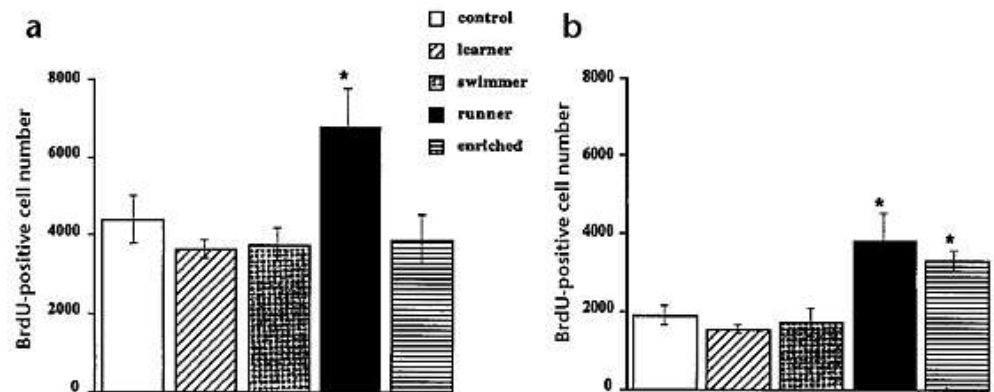
What is adult neurogenesis?

- Robust process
 - Thousands of new neurons integrate into dentate gyrus monthly



What is adult neurogenesis?

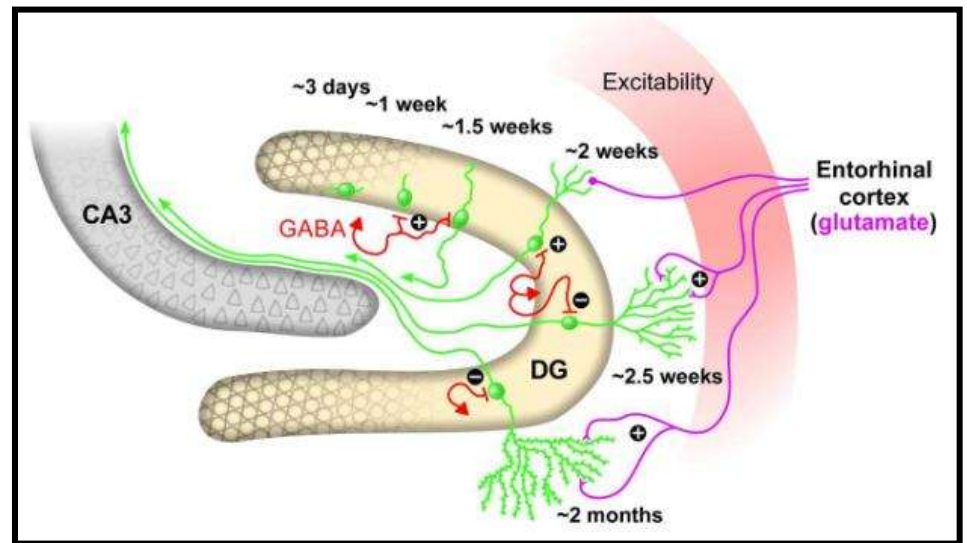
- Robust process
- Highly regulated
 - Both proliferation and survival controlled
 - Activity, enrichment, stress, diet, aging, disease...



van Praag et al., 1999

What is adult neurogenesis?

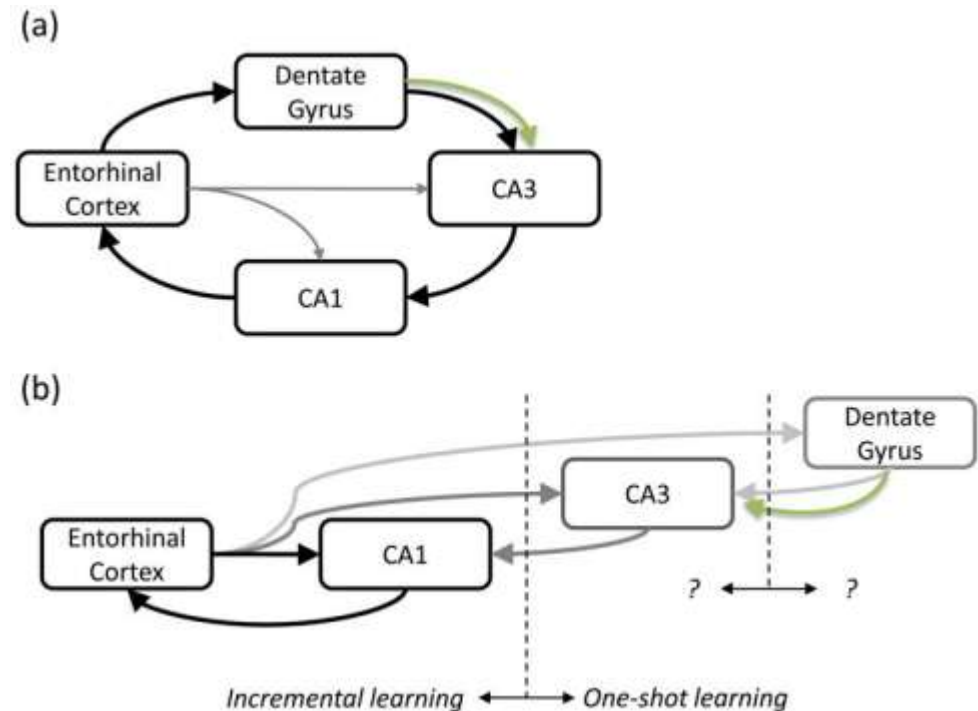
- Robust process
- Highly regulated
- Extended maturation
 - Several weeks to begin integrating into circuit
 - Still “immature” several months later



Aimone et al., Nature Neuroscience 2006

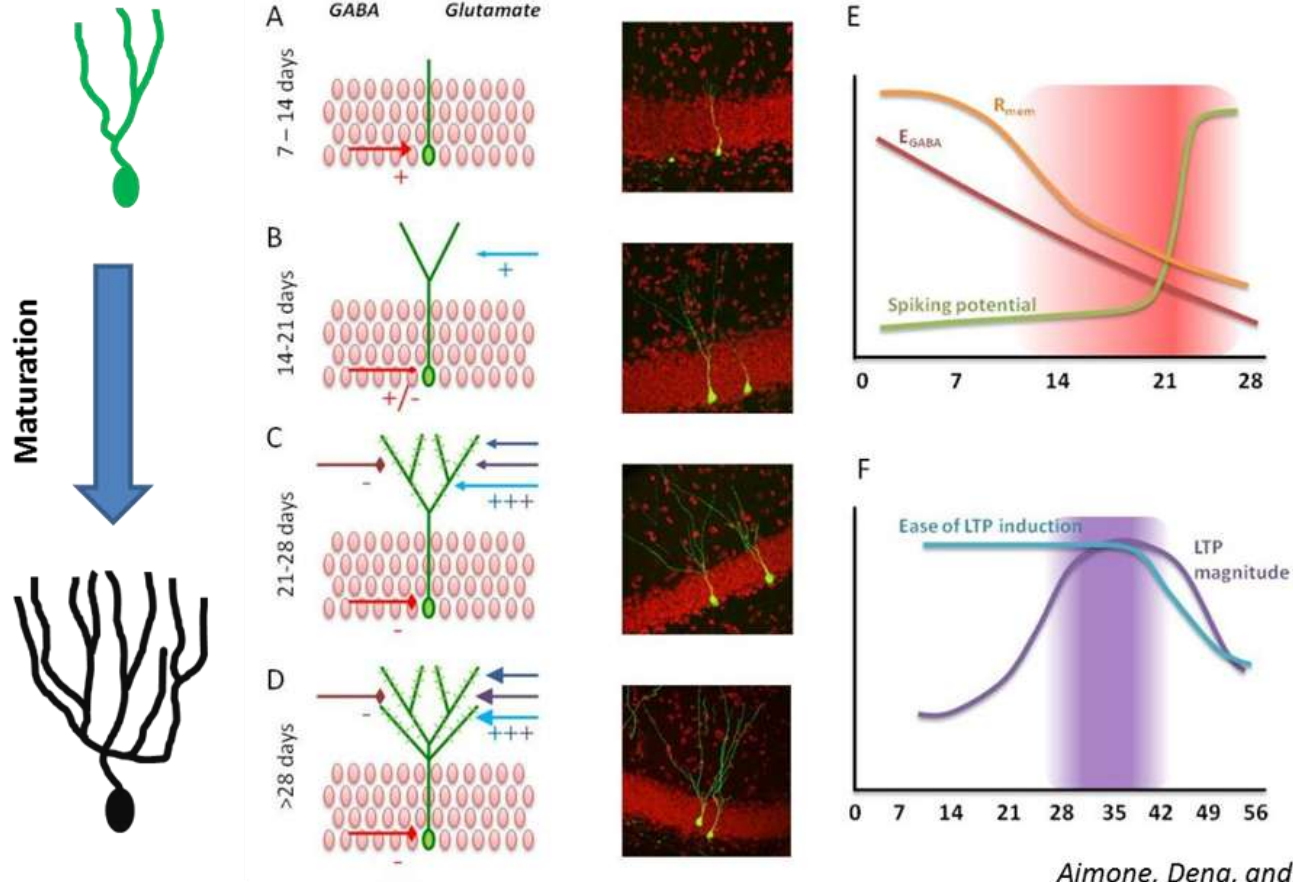
What is adult neurogenesis?

- Robust process
- Highly regulated
- Extended maturation
- Positioned to make an impact
 - Dentate gyrus is initial stage of hippocampus
 - Network amplifies effect of new neurons



*Aimone, Deng and Gage
Trends in Cog. Sci., 2010*

Maturation process of new neurons

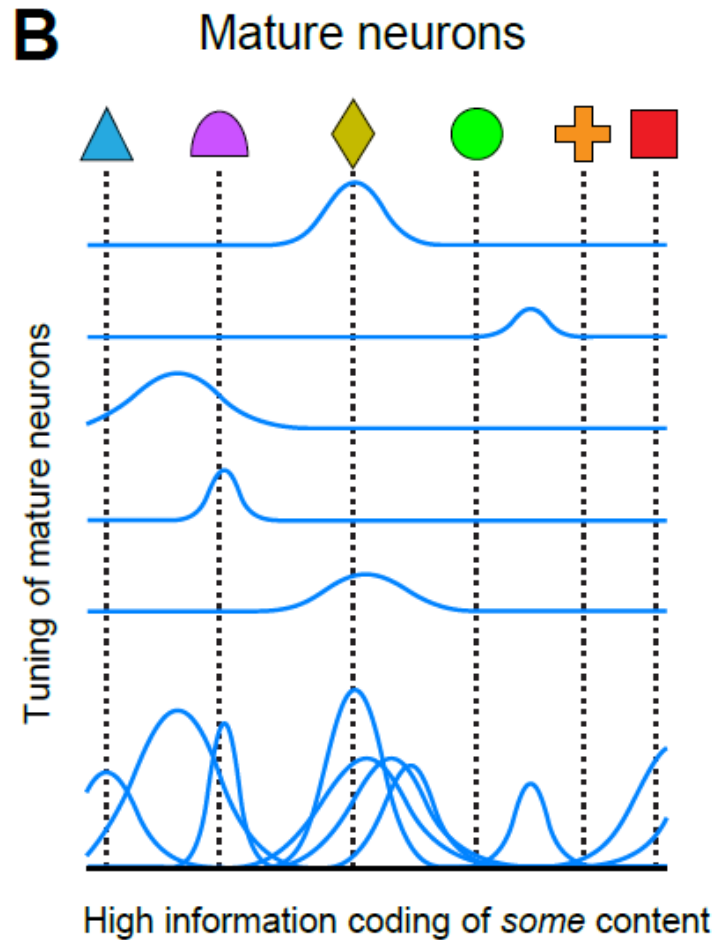
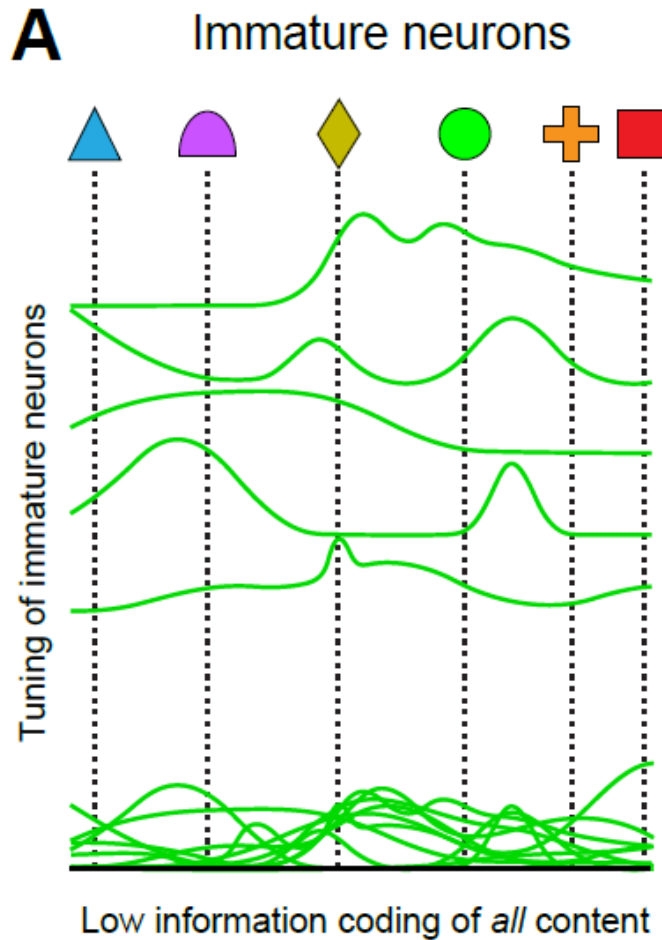


Aimone, Deng, and Gage
Trends in Cog. Sci. 2010

Adult Neurogenesis: Two Big Questions

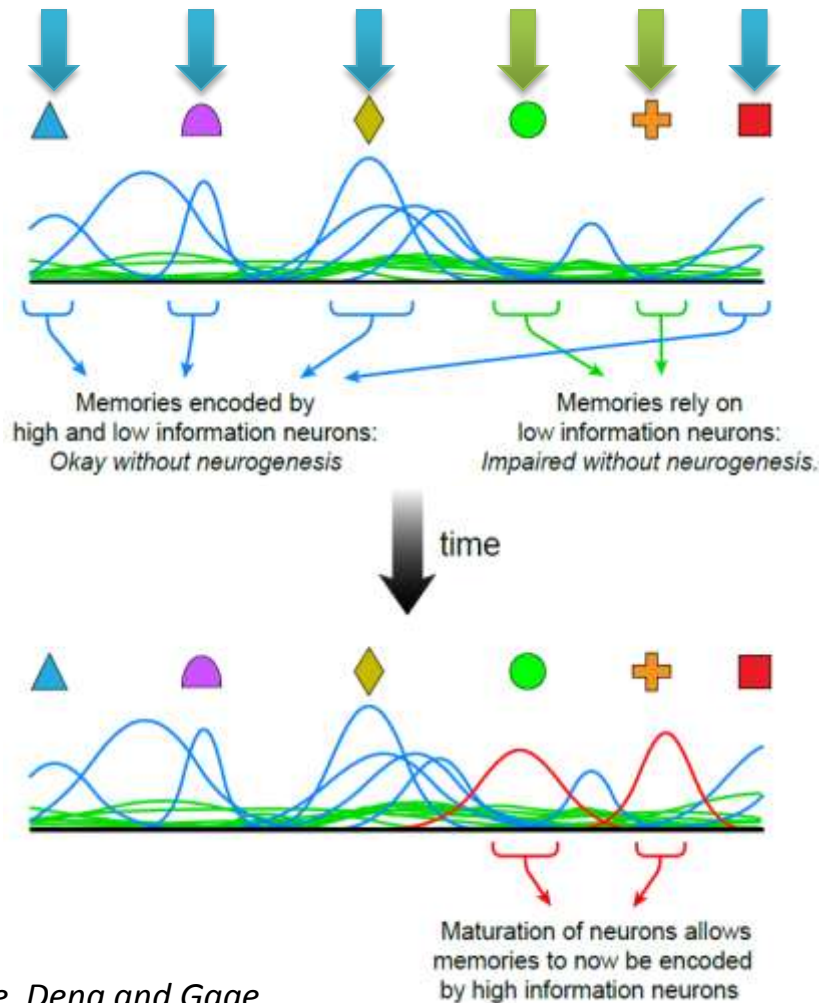
- What does it do for cognition?
- Relevant in humans?

Immature and mature neurons encode information differently



*Aimone, Deng and Gage
Neuron; 2011*

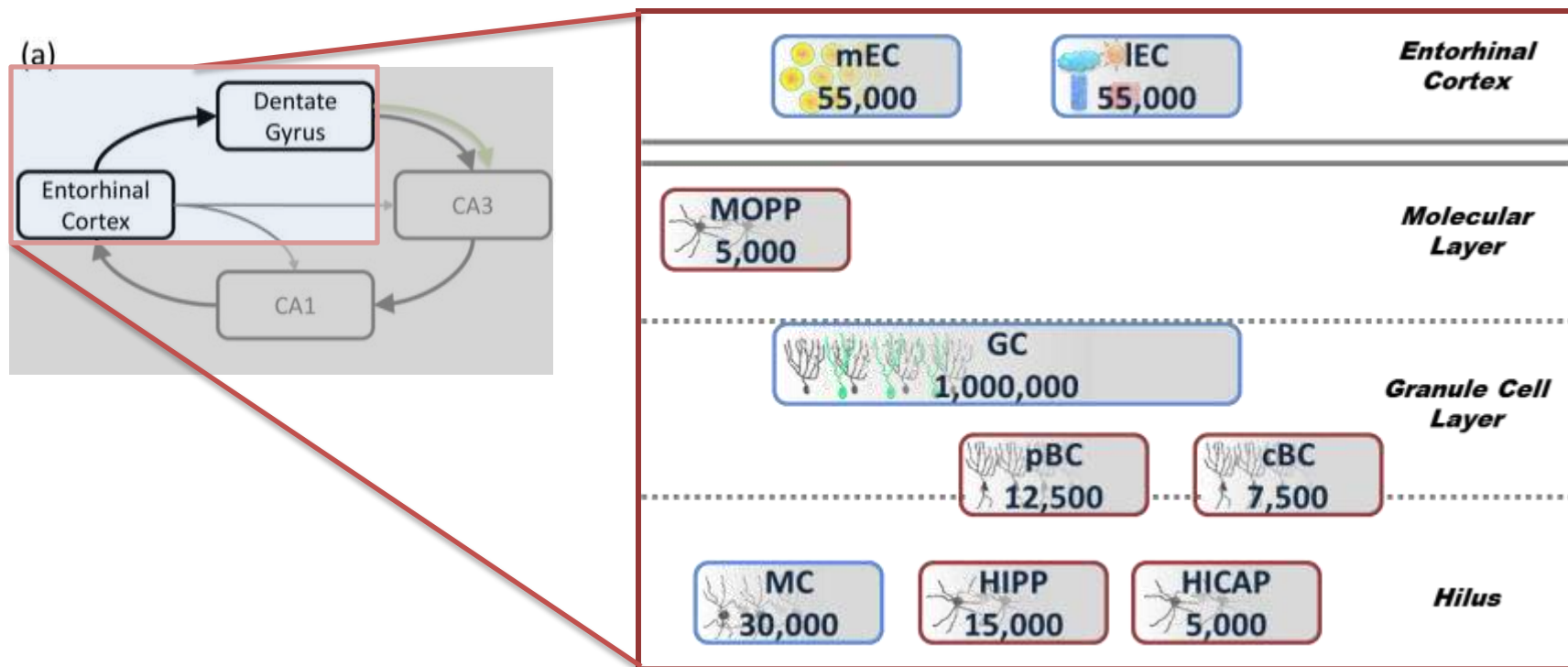
Mixed coding scheme in DG is potentially very powerful



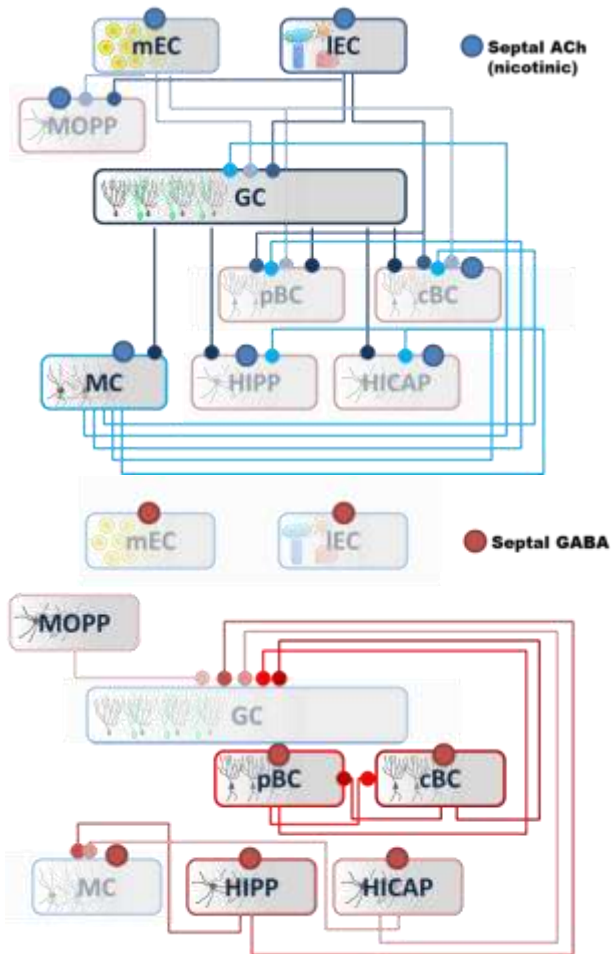
- Dentate Gyrus performs sparse coding for episodic memories
- Mature neurons are tightly tuned to specific features
 - *Not all events will activate mature neurons*
- Immature neurons are broadly tuned
 - *All events will activate some immature neurons*
- Neurons mature to be specialized to those events later
 - *Coding range of network gets more sophisticated over time*

Aimone, Deng and Gage
Neuron; 2011

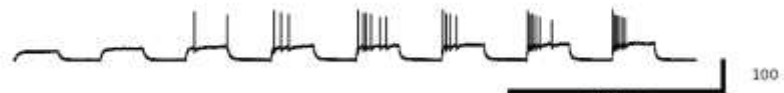
Realistic scale model



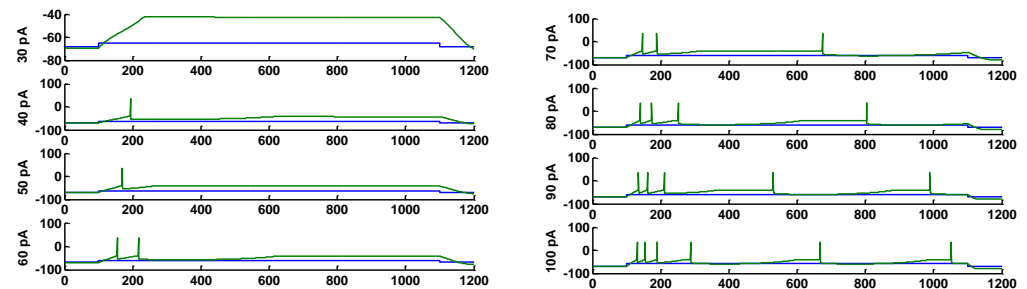
Realistic connectivity and dynamics



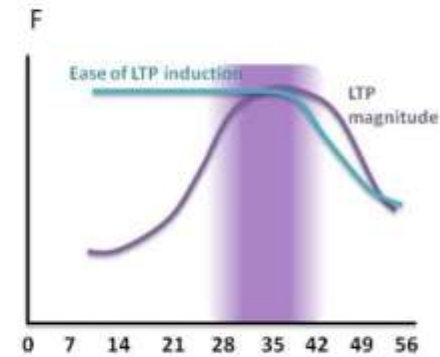
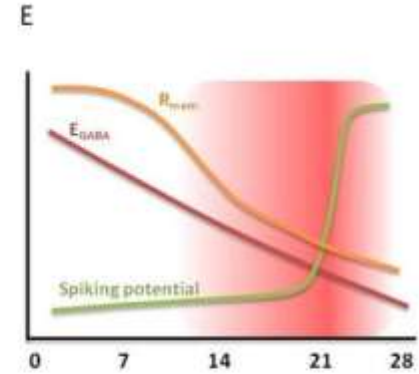
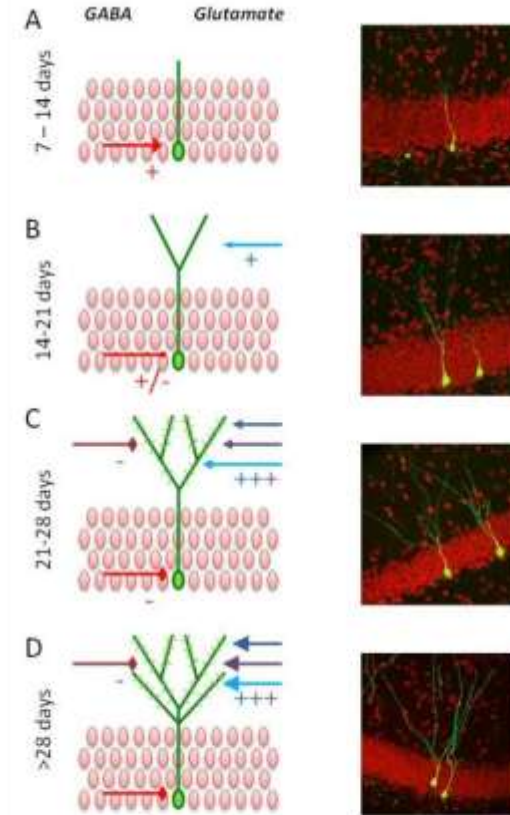
Physiology data



Modeled neuronal dynamics

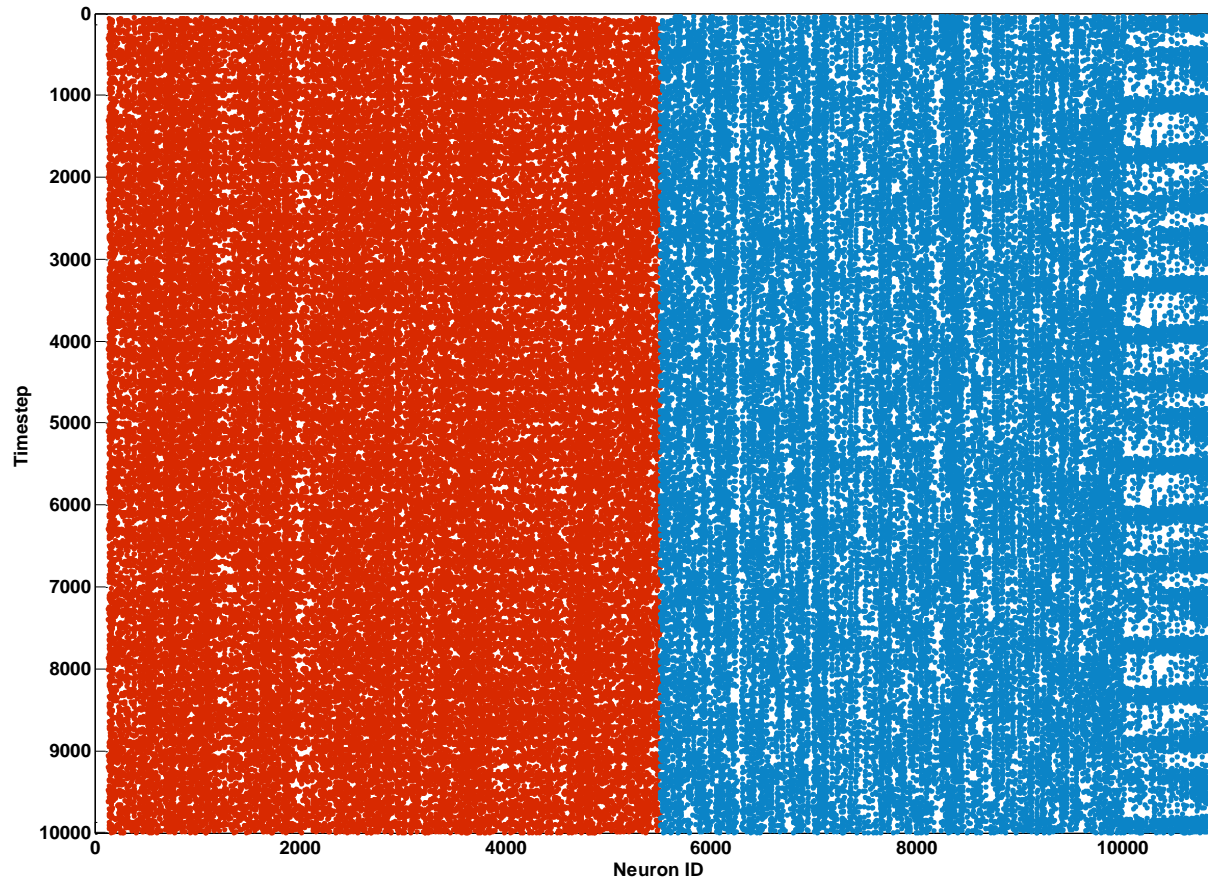


Neurogenesis Process

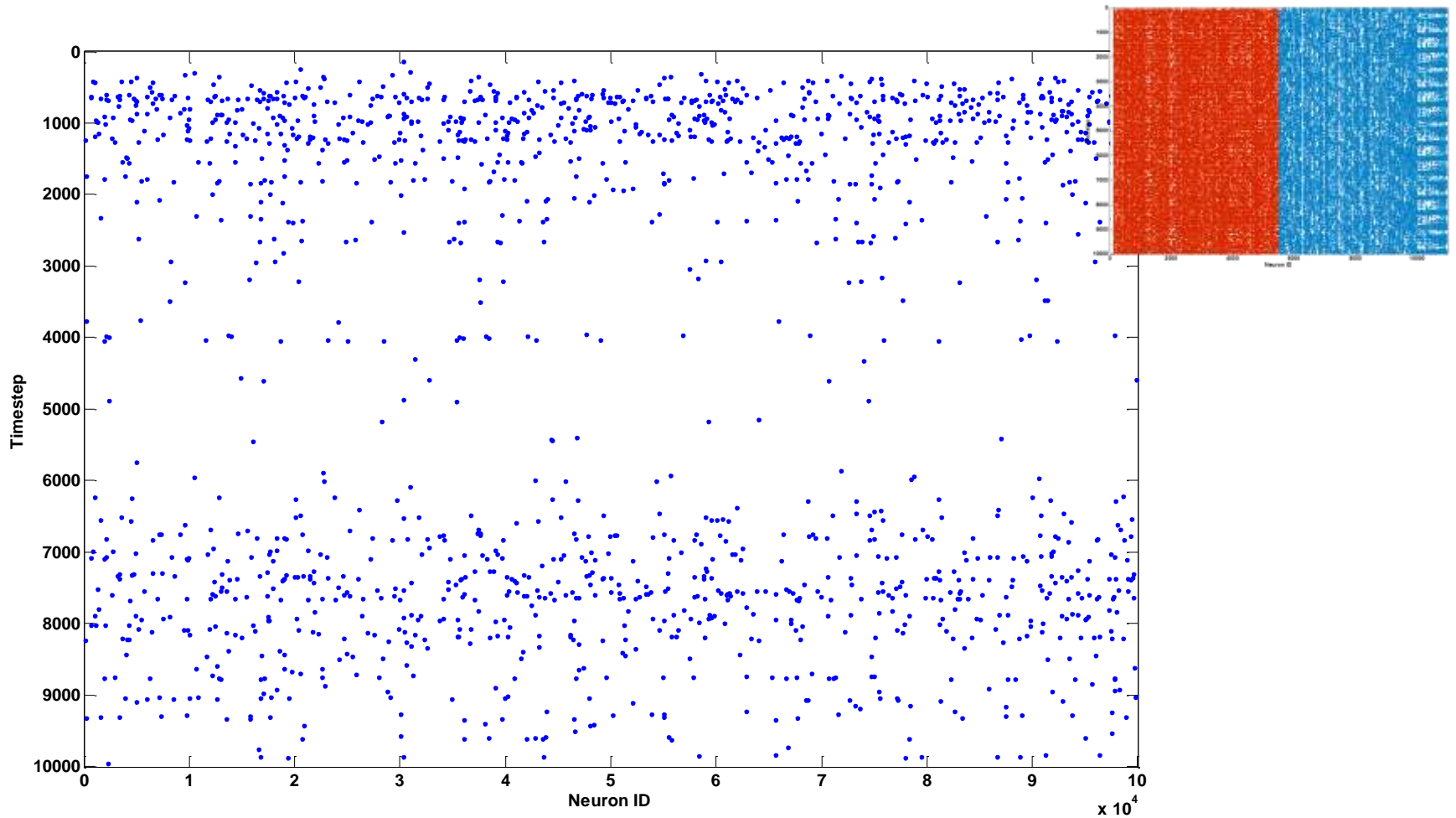


Aimone, Deng, and Gage
Trends in Cog. Sci. 2010

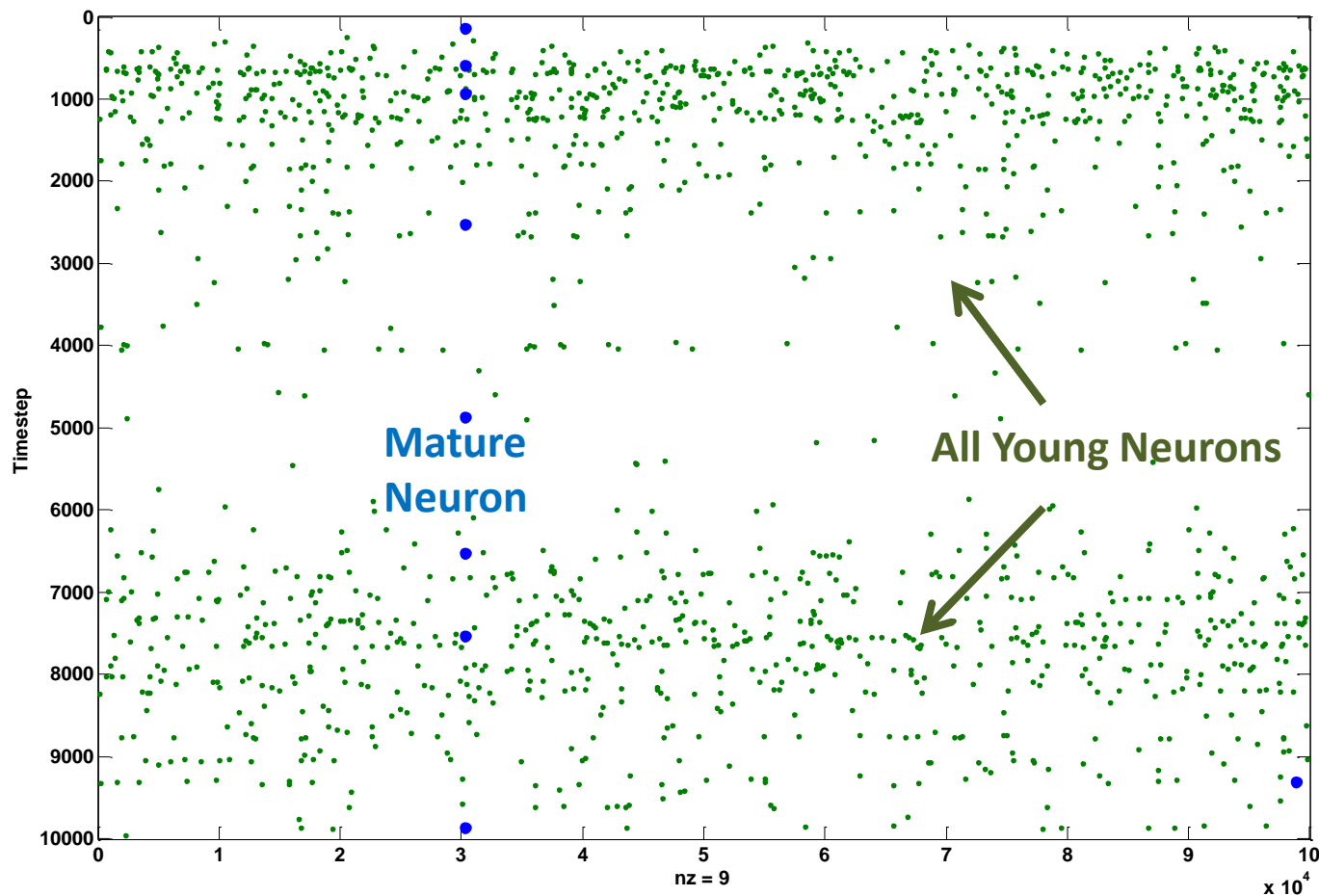
Activity of network – EC Inputs



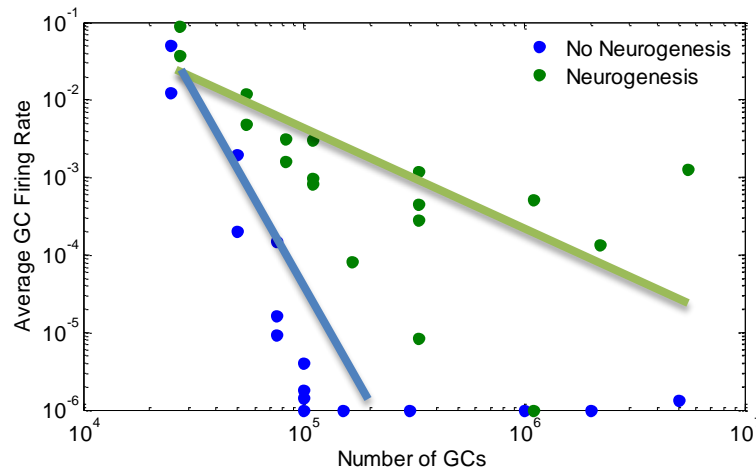
Activity of network – GC Outputs



Young GCs dominate

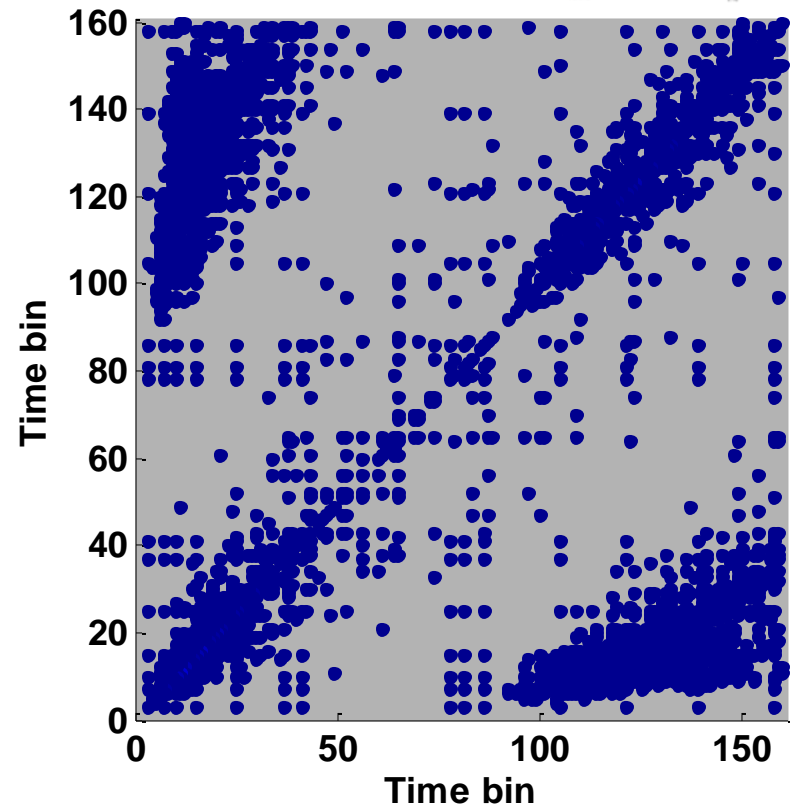
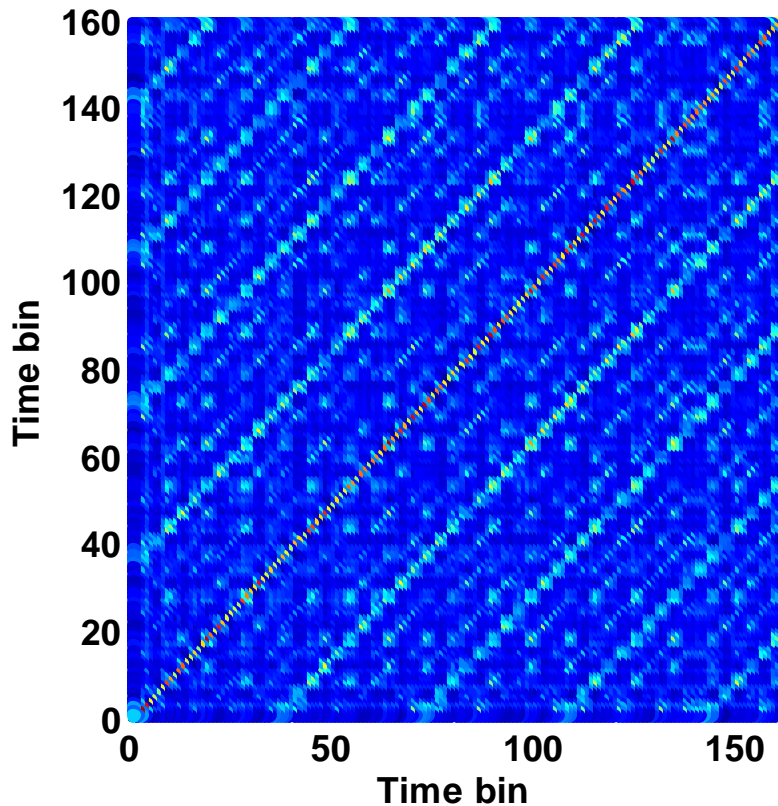
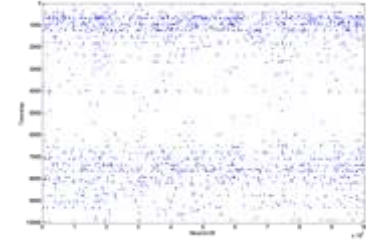
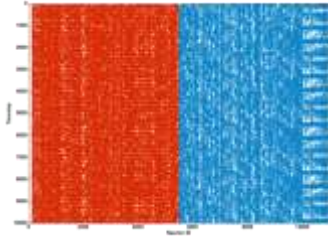


Lack of neurogenesis in large networks correlates with much lower activity

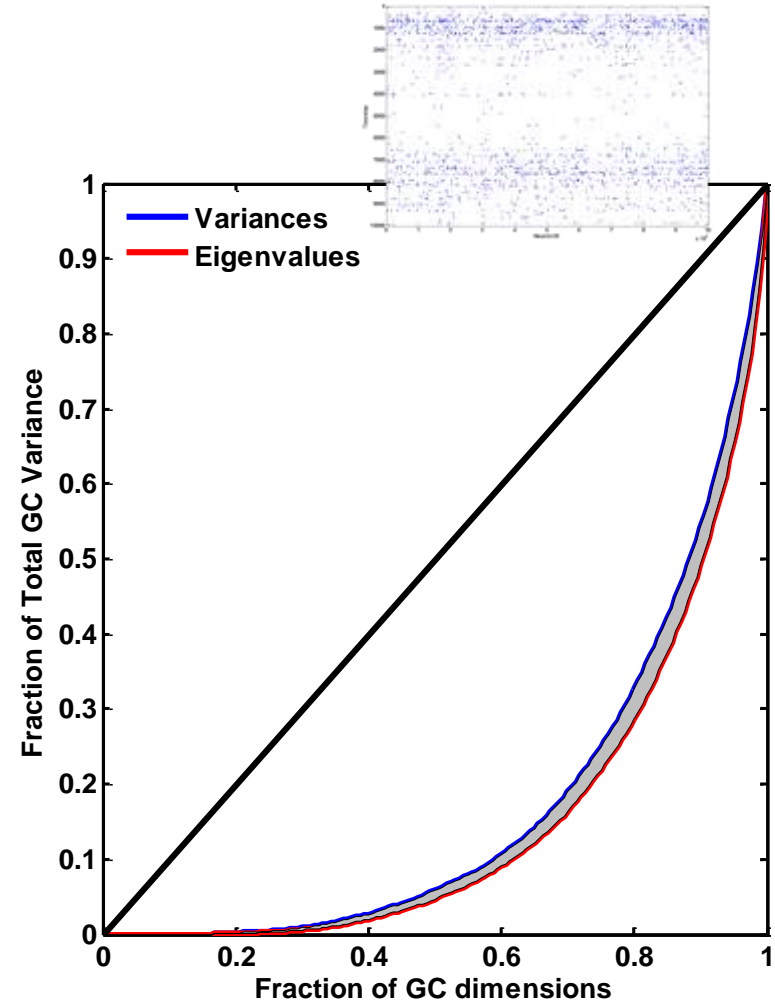
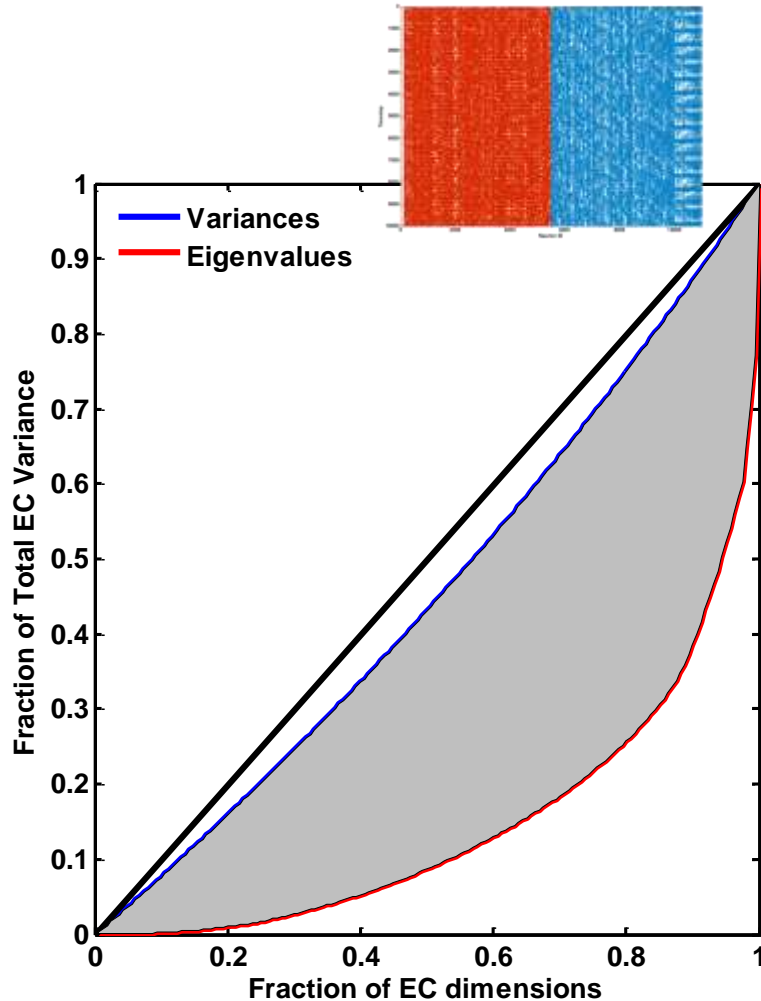


- Neurogenesis networks show activity to novel information at much higher scales
- As we approach human scales, mature neurons appear essentially silent in response to novel information
- Signal (immature) to noise (mature) is amplified in larger networks

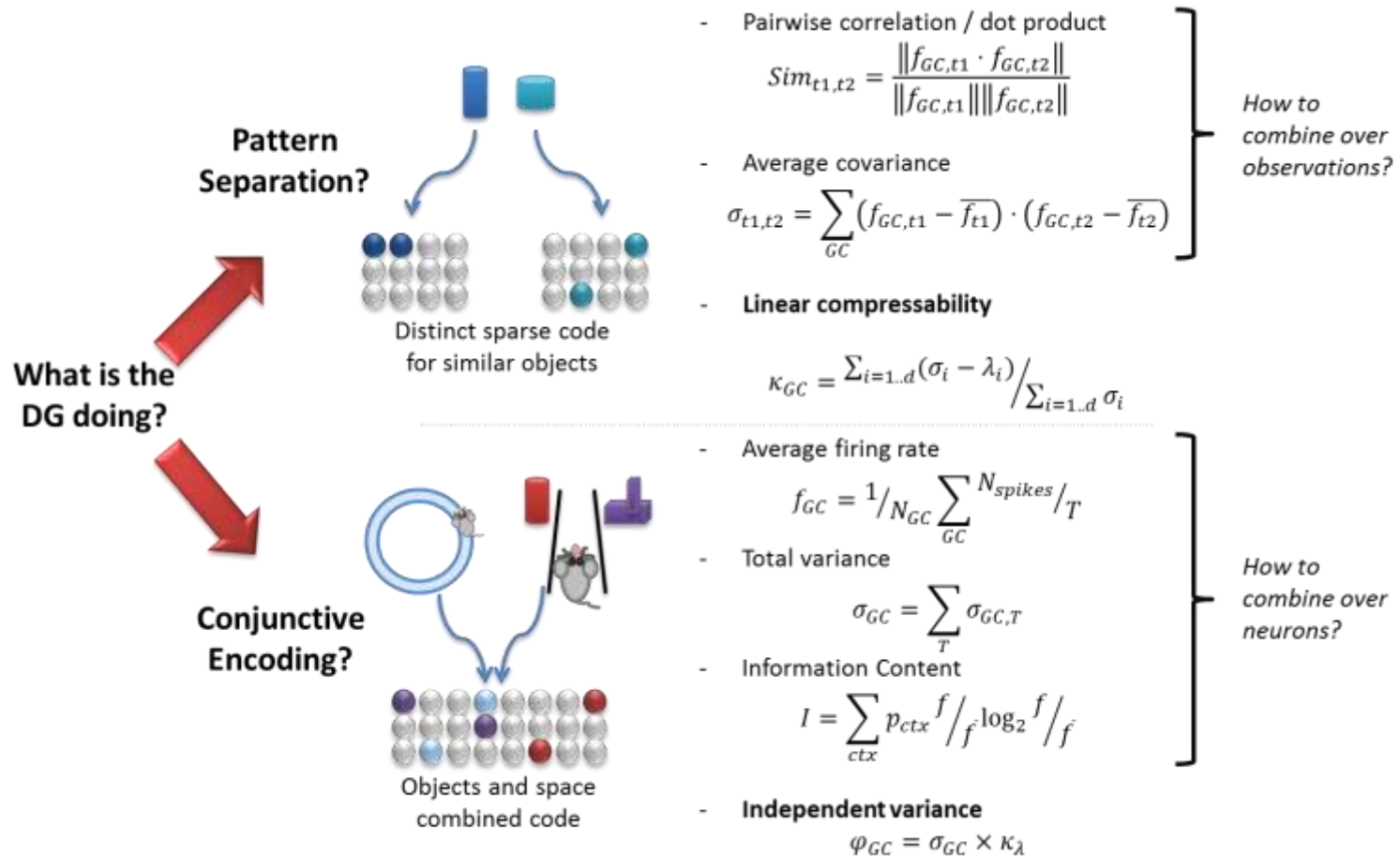
Information processing in large networks



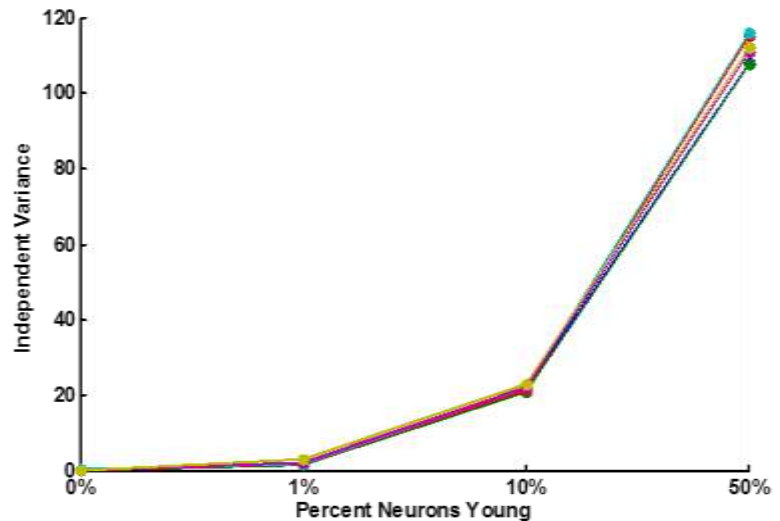
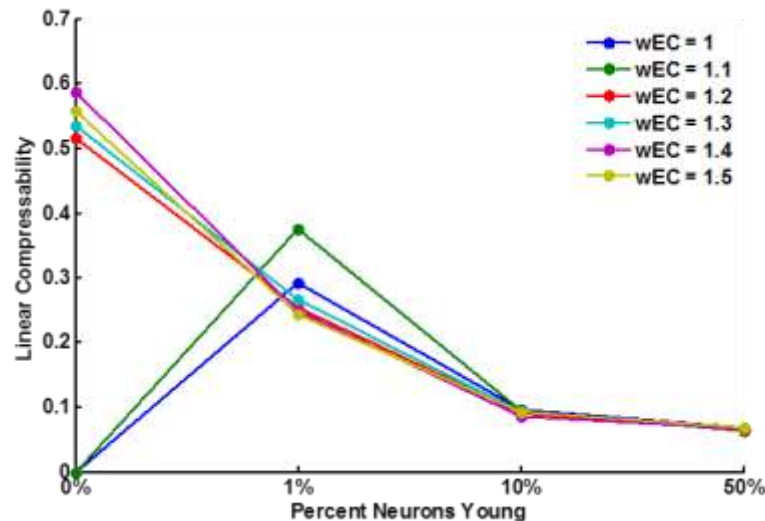
Information processing in large networks



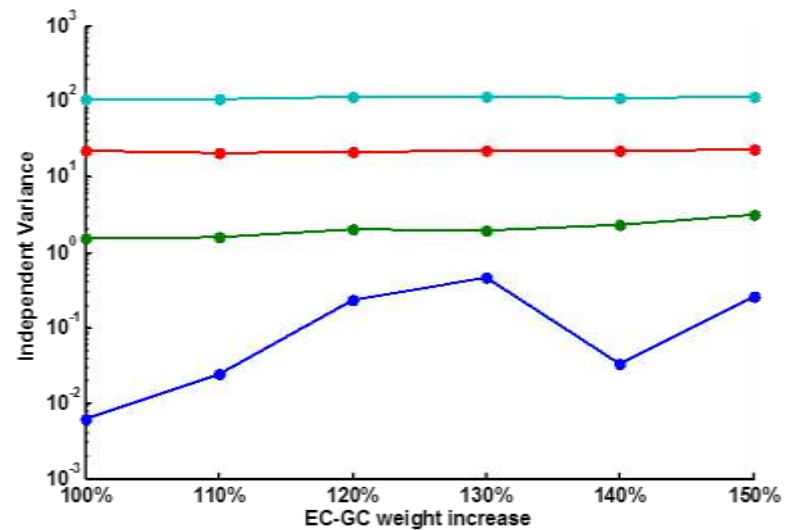
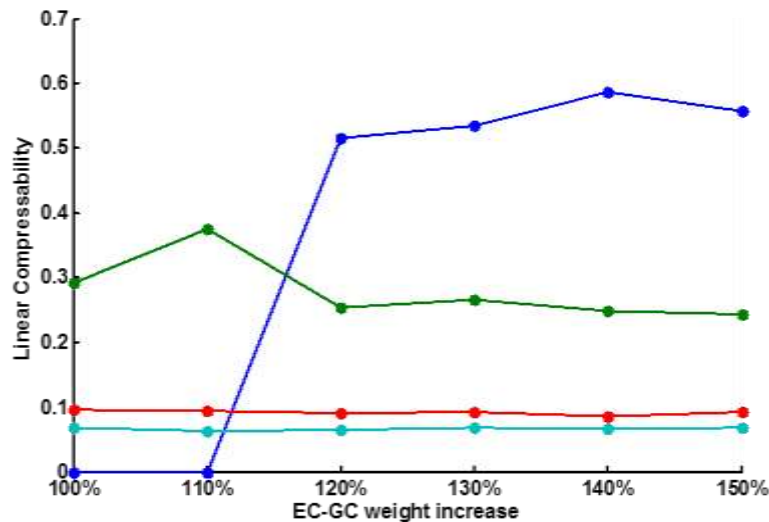
Metrics for understanding NG model



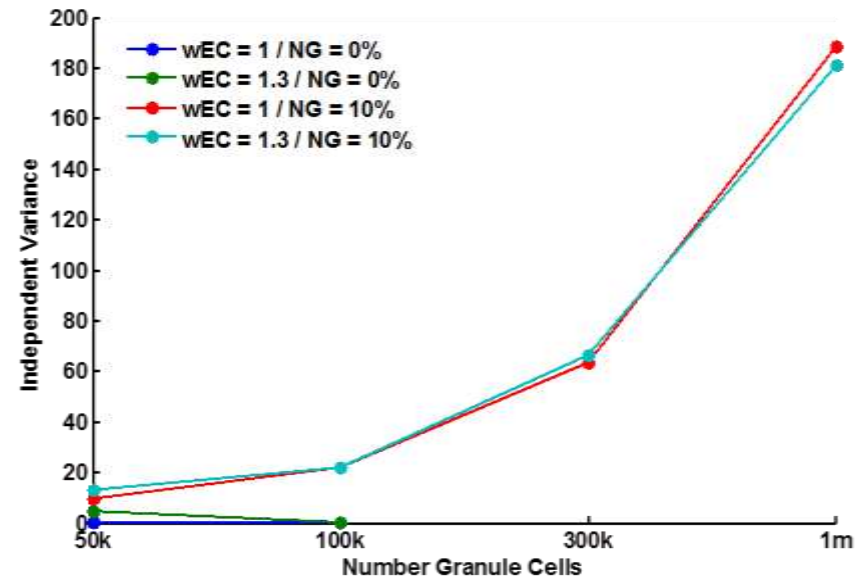
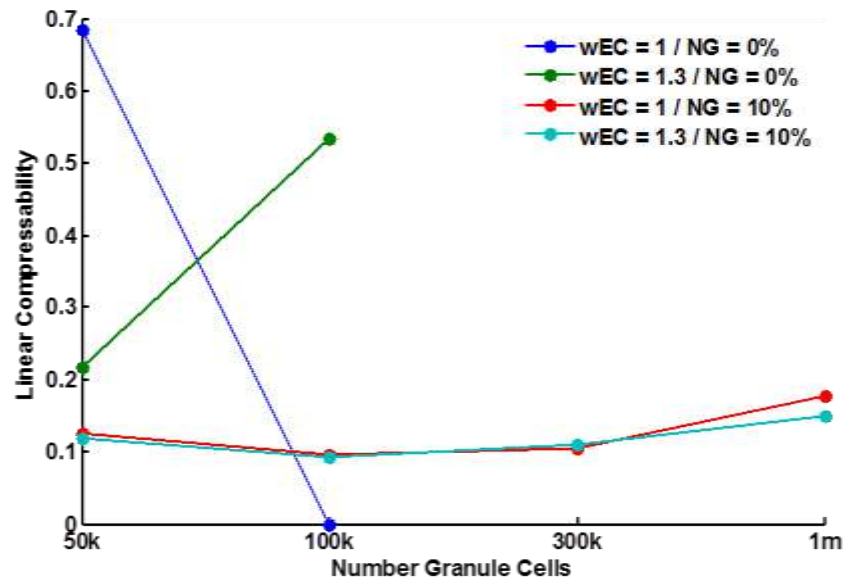
Neurogenesis decreases compressibility and increases total representation



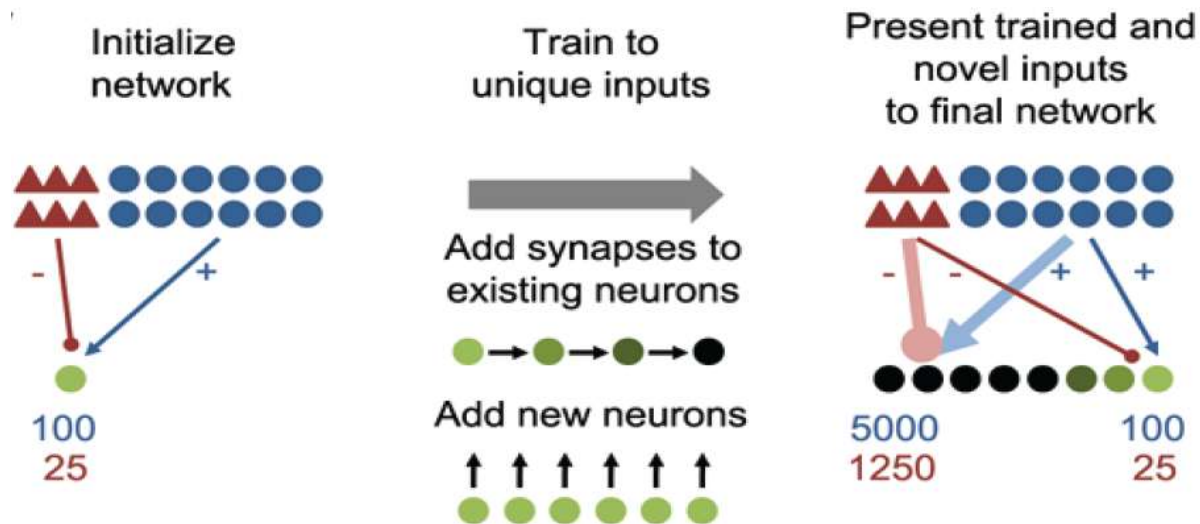
Increasing EC-GC weights impairs separation without improving coding



Increased size networks need neurogenesis for balancing separability and representations



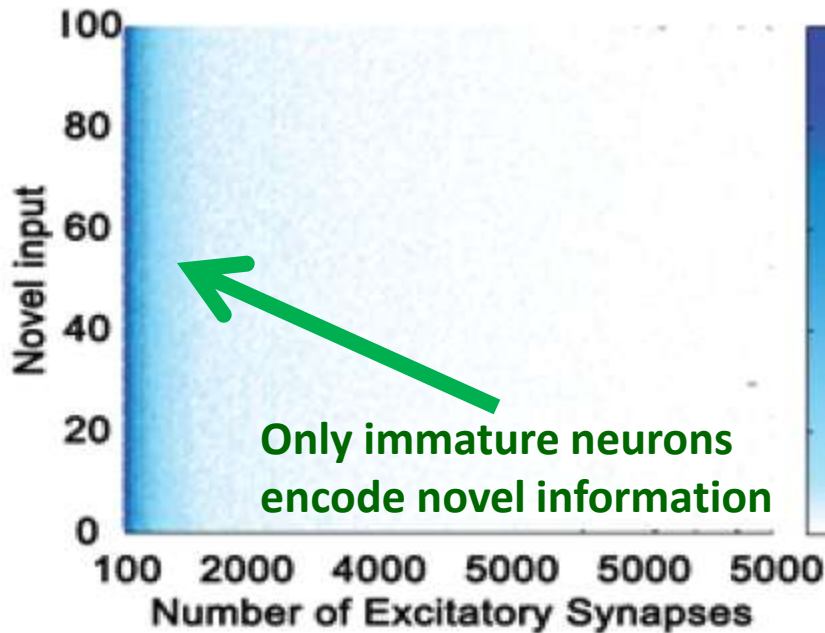
Abstract model: scaling neuron sizes yields neurogenesis effect



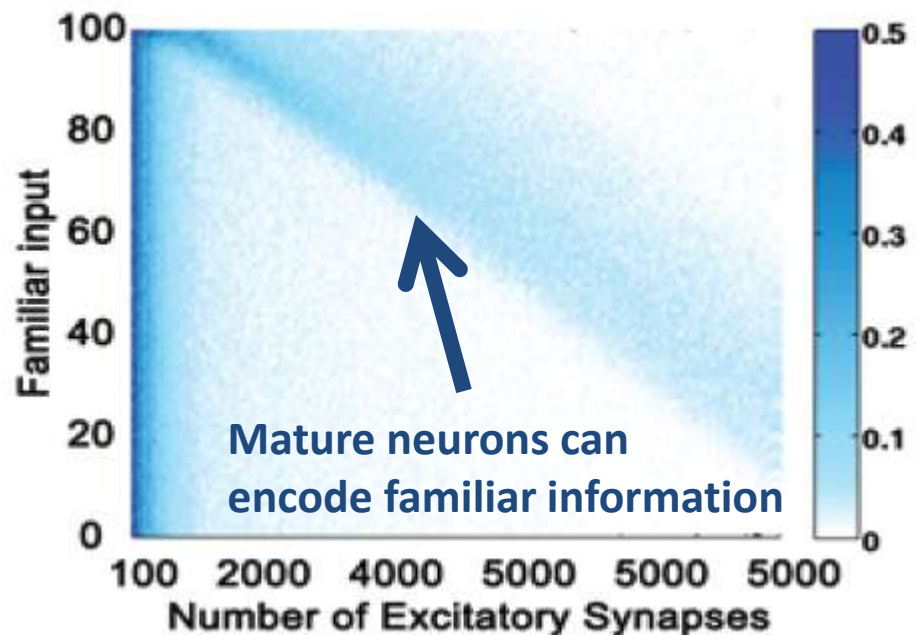
Li, Aimone et al., PNAS 2012

Neurons maturing to large number of synapses contain high information about maturation cues

Novel Inputs

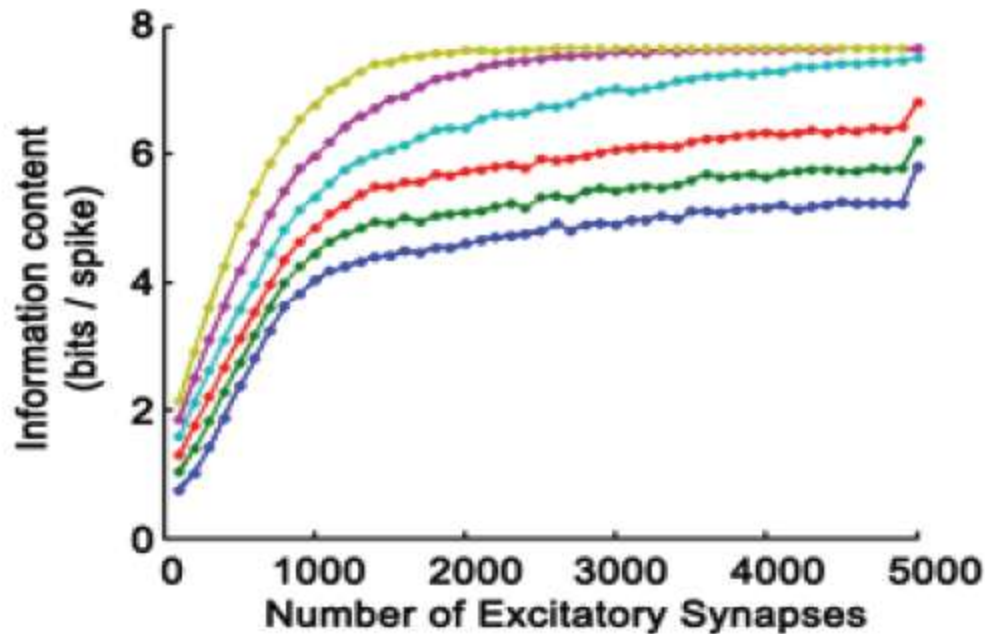


Trained Inputs



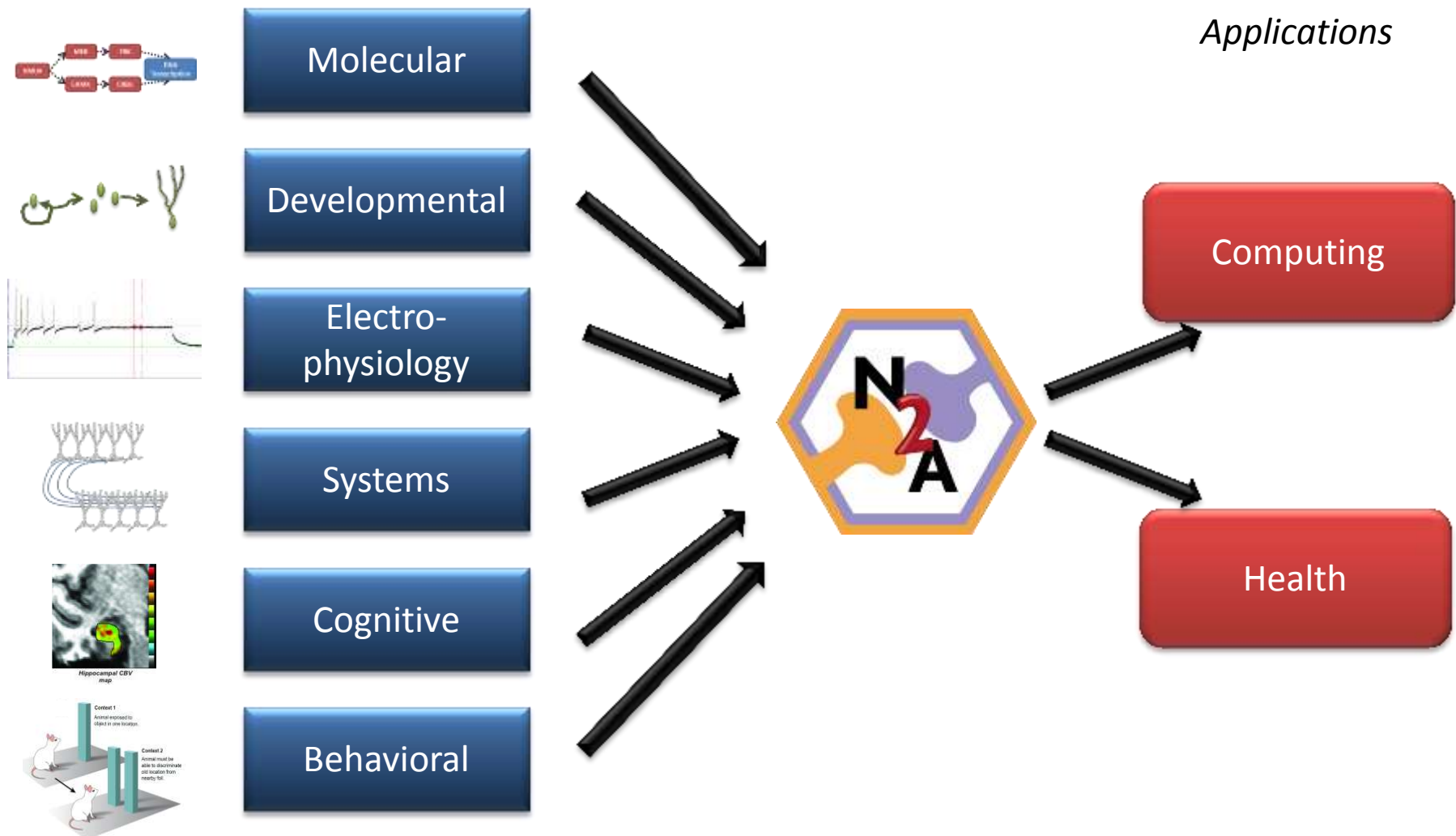
Li, Aimone et al., PNAS 2012

High synapse neurons have higher information content



Li, Aimone et al., PNAS 2012

Neuroscience to Applications



The Challenge



Society for Neuroscience
>30,000 scientists attend
>1,000 topic areas presented

Need to integrate all this knowledge. Beyond capacity of anyone to comprehend.

The community needs powerful computer tools, which Sandia has to offer.

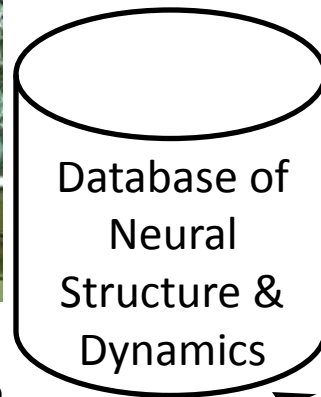
In return, the community will give us far richer models (crowd-sourcing) that we can leverage in mission applications.

How we do it



- Contributed models
- Neurophysiology literature
- Online databases

- Visualization
- Automatic analysis



Simulate



Fit parameters

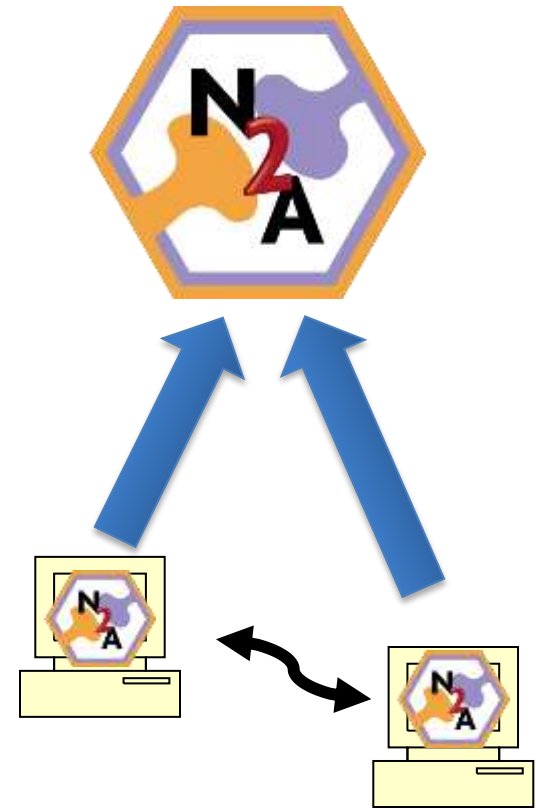
Characterize model behavior

Algorithmic motifs

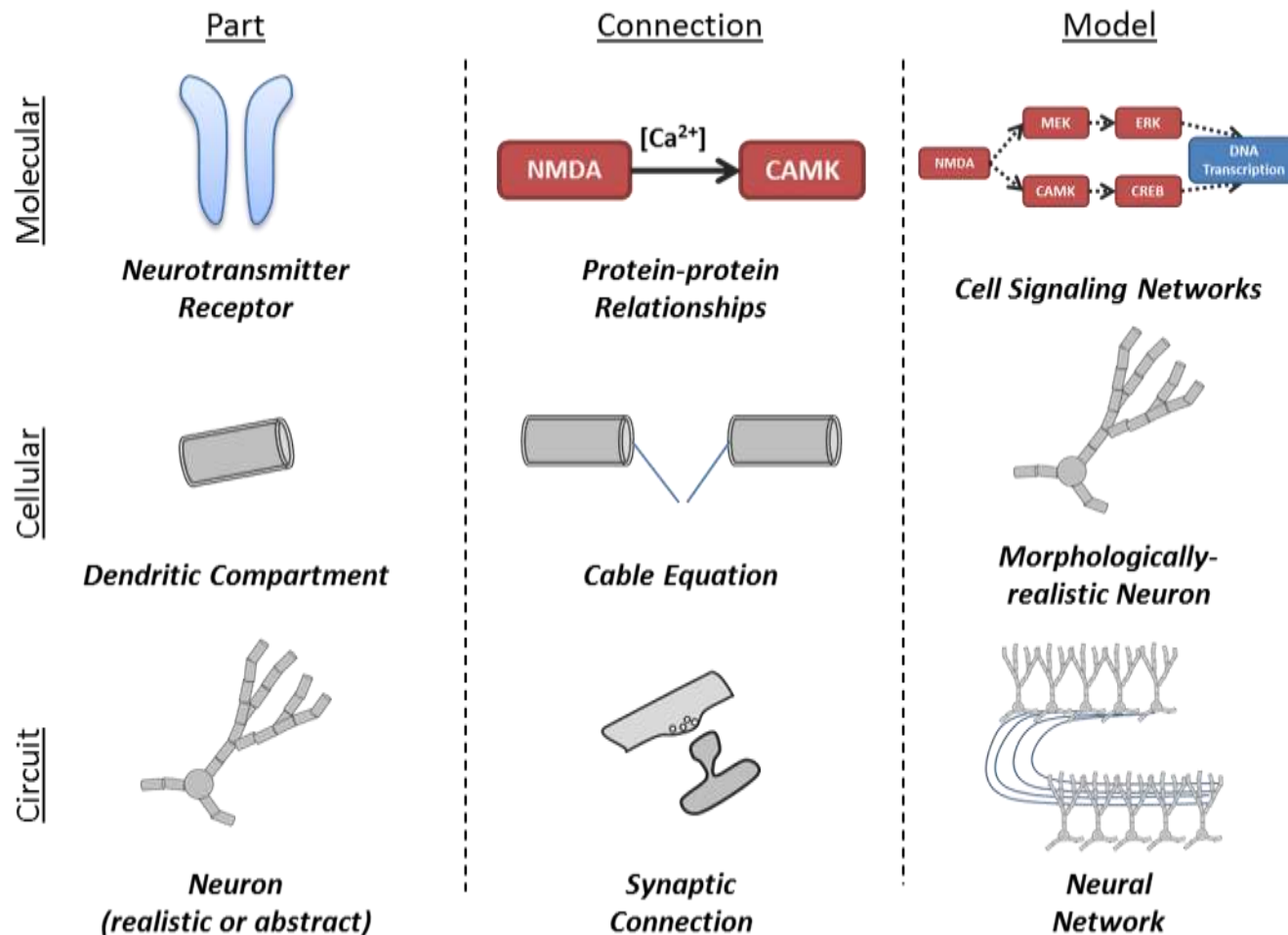


N2A Vision

- Open Source
- Peer-to-peer model sharing
- Versioning of models (repeatability)
- Sensitivity Analysis and Streamlined Parameter Estimation
- Interface into Neuroinformatics tools and frameworks (e.g., NeuroML, NIF)
- Ability to incorporate existing published models



Different scales, same approach



Model Structure

Dynamical Systems
AND Parts-Relations

Many things can be
modeled in this form,
including biology and
cognition.

Connection

$$\begin{aligned}A.V' &+= B.V - A.V \\ B.V' &+= A.V - B.V \\ &\dots\end{aligned}$$

Structural dynamics:
express quantity and
arrangement of Parts,
as well as their internal
state.

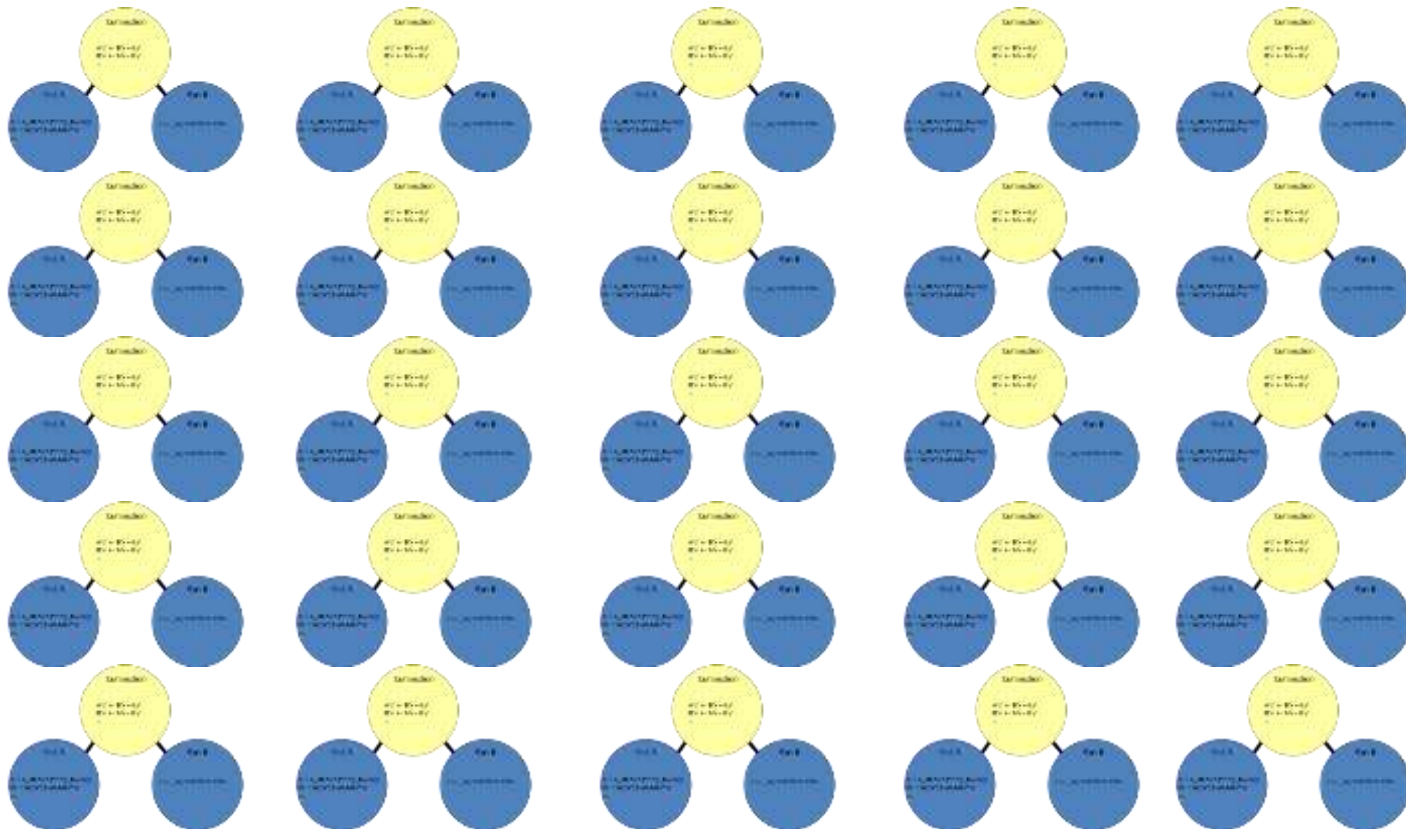
Part A

$$\begin{aligned}V' &= G_Na * m^3 * h * (E_Na - V) / C \\ m' &= \alpha * (1 - m) - \beta * m \\ &\dots\end{aligned}$$

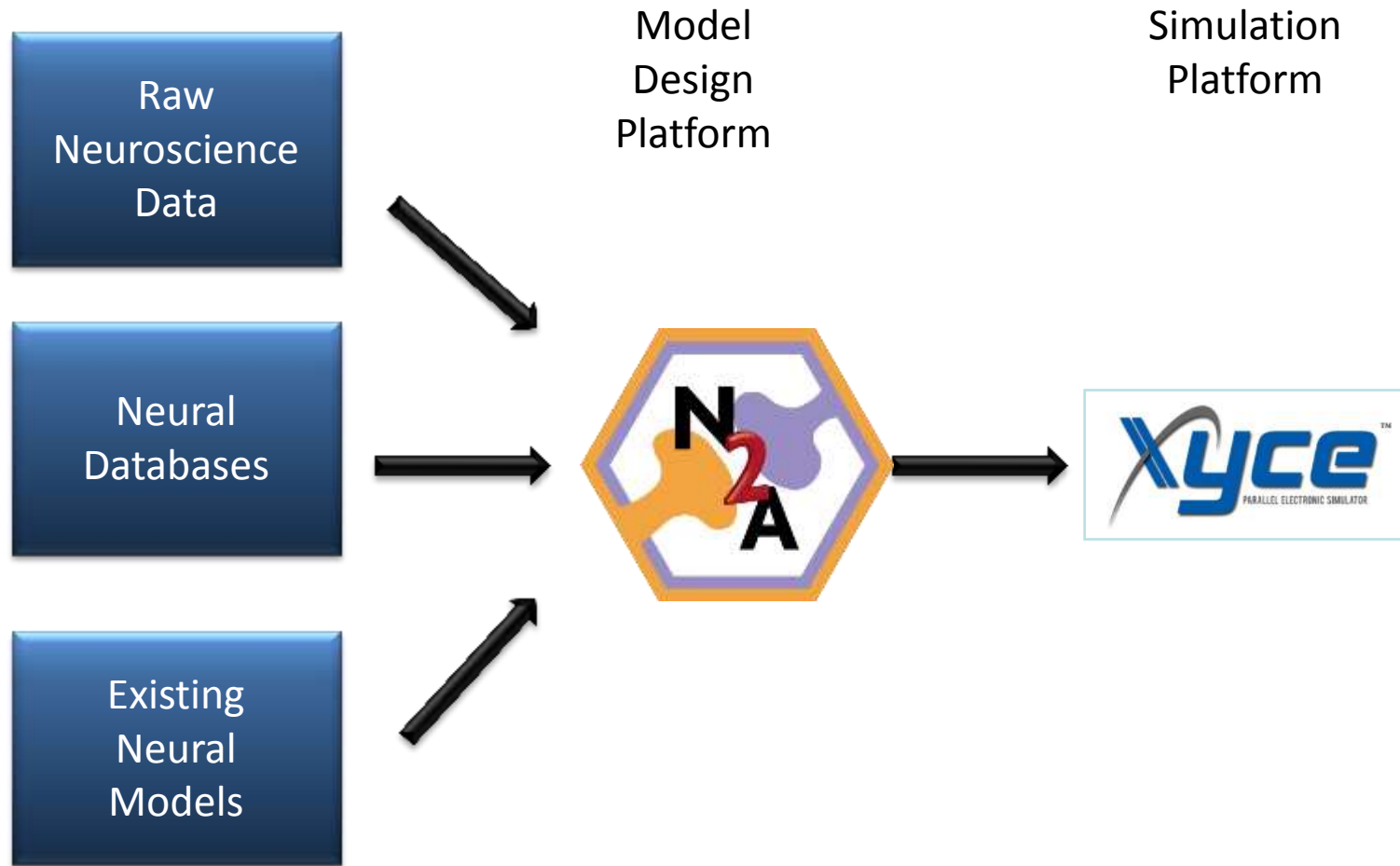
Part B

$$\begin{aligned}V' &= I_inj + 0.04 * V^2 + 5 * V + \dots \\ &\dots\end{aligned}$$

Multiple instantiations to scale up model



Sandia Computational Neuroscience Tools



Sandia's Computing Strengths

Device Physics
Parallel Network Creation
Time Integration
Parallel Analysis



Sampling
Optimization
Sensitivity
Job control



Parallel & Serial Solvers
Parallel Data Structures
Multicore / Parallel Linear Algebra
Nonlinear Solvers
Parallel Graph Partitioning

Sandia R&D expertise covers many levels important to computational neuroscience.
Can we leverage this for Xyce and Computational Neuroscience?

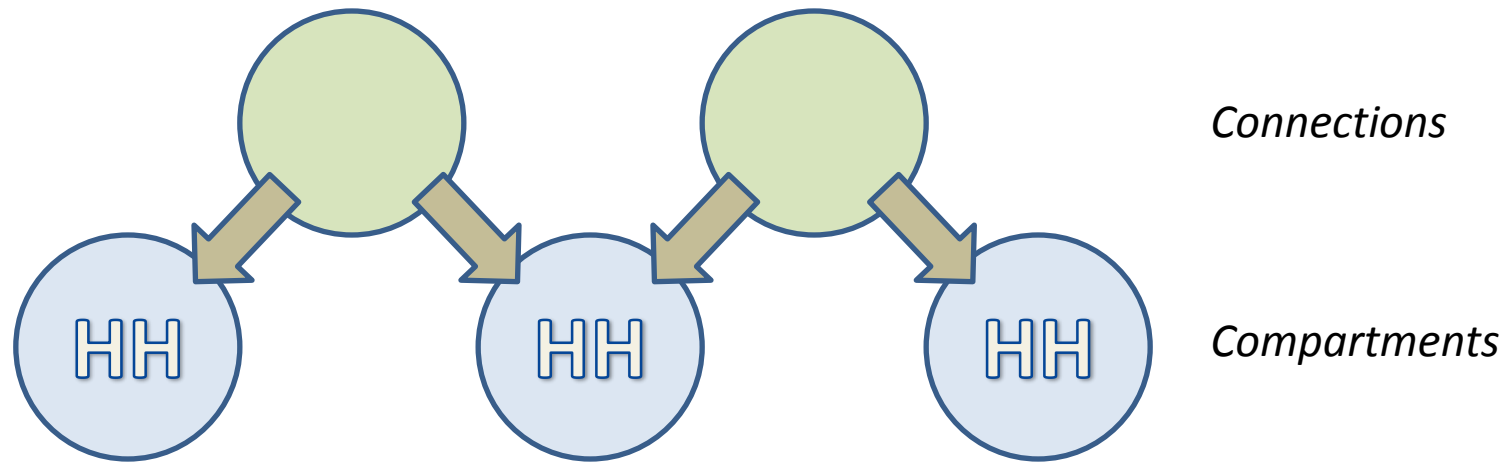
N2A Demo – Example Problem

Measure Spike Propagation through Multi-Segment Hodgkin-Huxley Cable

Neuroscientist Representation:



N2A Representation:



N2A - Demo

Neurons To Algorithms v0.8.4

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General Parent Equations Includes Notes/Tags Uses Discussion Permissions References Change History Summary

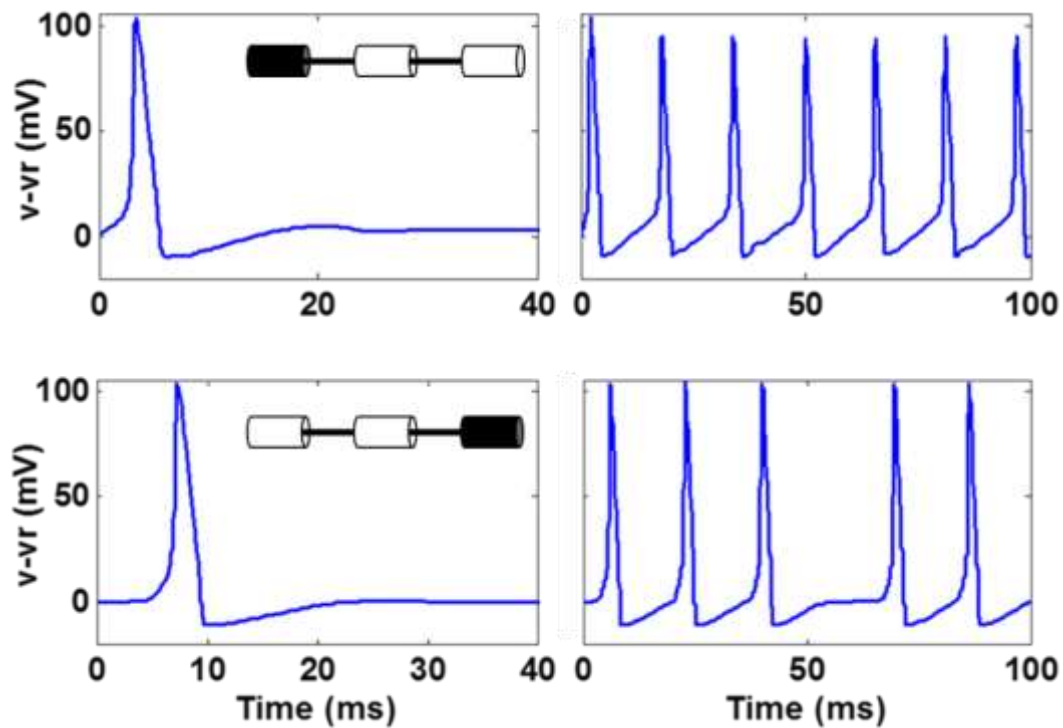
Summary: ? ☒ Tree ☐ Flat ☐ Text ☐ Graph ☐ Problems

All Equations For "HHmod"

- Inherited Equations
 - Parent: passive
 - $V' = (G_m * (V_{rest} - V) + I_{inj}) / C_m$
 - $G_m = 0.3$
 - $V_{rest} = 10.613$
 - $C_m = 1$
- Included Equations
 - Na_Koch (alias: Na_Koch)
 - $I = G_{Na} * m^3 * h * (E_{Na} - V)$
 - $m' = \alpha_m * (1 - m) - \beta_m * m$
 - $h' = \alpha_h * (1 - h) - \beta_h * h$
 - $\alpha_m = (25 - V) / (10 * (\exp((25 - V) / 10) - 1))$
 - $\beta_m = 4 * \exp(-V / 18)$
 - $\alpha_h = 0.07 * \exp(-V / 20)$
 - $\beta_h = 1 / (\exp((30 - V) / 10) + 1)$
 - $G_{Na} = 120$
 - $E_{Na} = 115$
 - K_Koch (alias: K_Koch)
 - $I = G_K * n^4 * (E_K - V)$
 - $n' = \alpha_n * (1 - n) - \beta_n * n$
 - $\alpha_n = (10 - V) / (100 * (\exp((10 - V) / 10) - 1))$
 - $\beta_n = 0.125 * \exp(-V / 80)$
 - $G_K = 36$
 - $E_K = -12$

Connected to: jdbc:postgresql://mechta/n2a

Results



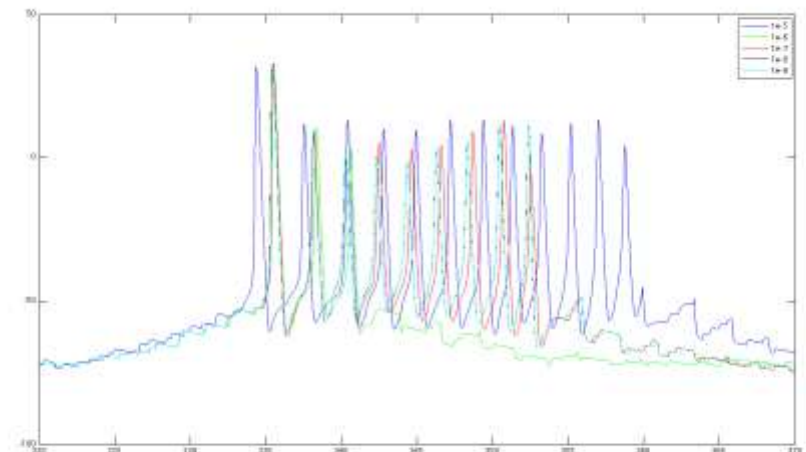
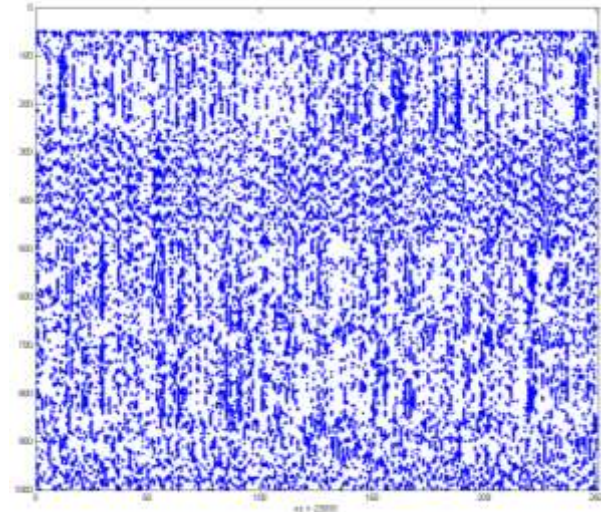
Sensitivity of recurrent spiking neural networks

1. Borderline chaotic dynamics

- Network is deterministic
- Very slight deviations in solving get amplified by spiking

2. How do you analyze?

- Individual neurons diverge over time
- Need “ground truth”



Recurrent model in N2A

Neurons to Algorithms v0.8.8.b20121113-1659

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Home Search Brette 80-20 cobahh

Model: *Brette 80-20 cobahh* Save Cancel

General
Dimensions
Topology
Inputs
Outputs
Equations
Notes/Tags
Discussion
Permissions
References
Change History
Runs
Summary

Layers: ?

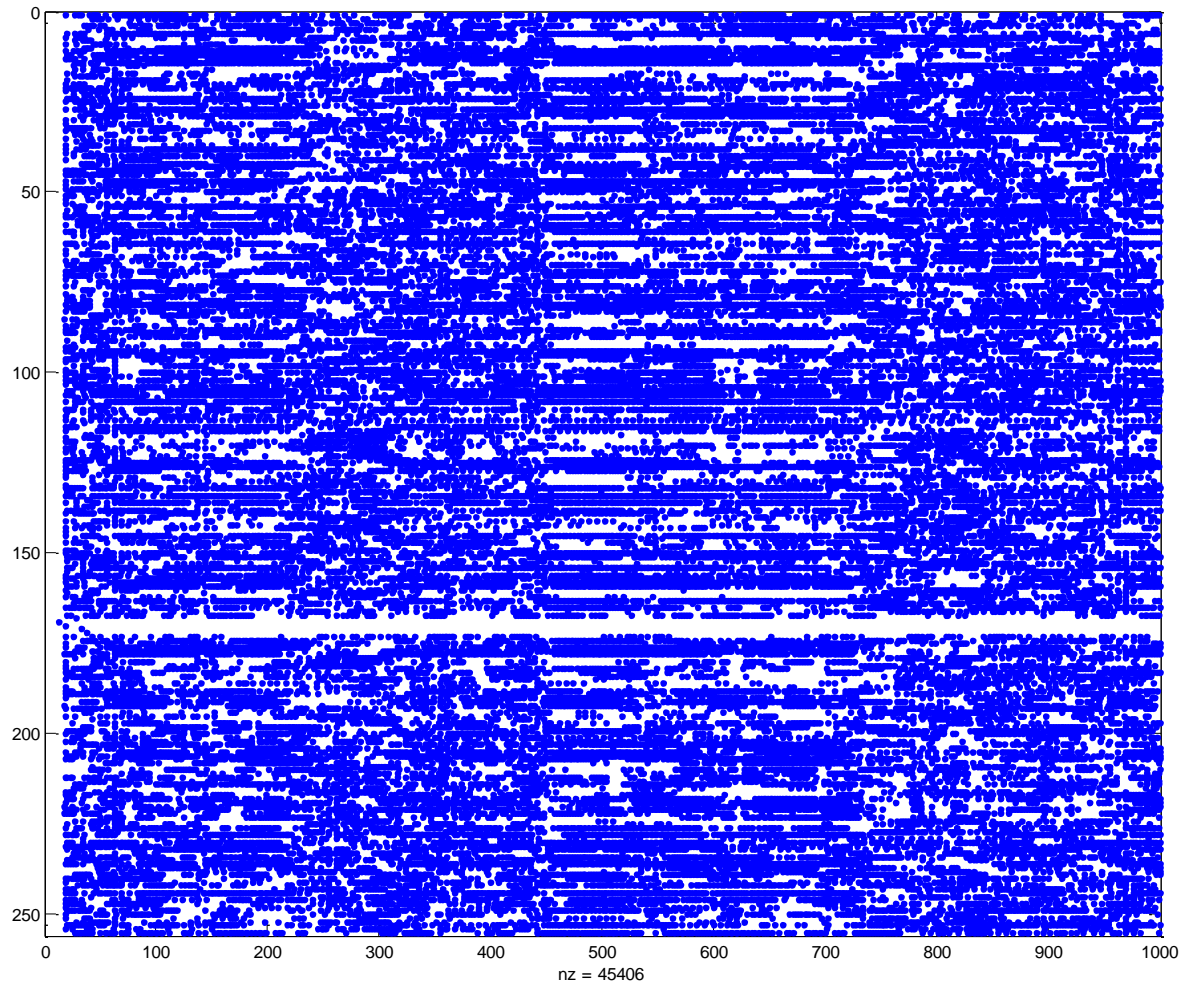
- AllCells (compartment: HH point neuron, Brette)
 - Layer Equations
 - Compartment Equations
 - $V' = (G_{Na} * m^3 * h * (E_{Na} - V) + G_K * n^4 * (E_K - V) + G_m * (V_{rest} - V) + I_{inj}) / C_m$
 - $m' = \alpha_m * (1 - m) - \beta_m * m$
 - $h' = \alpha_h * (1 - h) - \beta_h * h$
 - $n' = \alpha_n * (1 - n) - \beta_n * n$
 - $\alpha_m = 1000 * 0.32 * (13 - 1000 * V + VT) / ((\exp((13 - 1000 * V + VT) / 4) - 1))$
 - $\beta_m = 1000 * .28 * (1000 * V - VT - 40) / (\exp((1000 * V - VT - 40) / 5) - 1)$
 - $\alpha_h = 1000 * 0.128 * \exp((17 - 1000 * V + VT) / 18)$
 - $\beta_h = 1000 * 4 / (\exp((40 - 1000 * V + VT) / 5) + 1)$
 - $\alpha_n = 1000 * 0.32 * (15 - 1000 * V + VT) / ((\exp((15 - 1000 * V + VT) / 5) - 1))$
 - $\beta_n = 1000 * 0.5 * \exp((10 - 1000 * V + VT) / 80)$

Bridges: ?

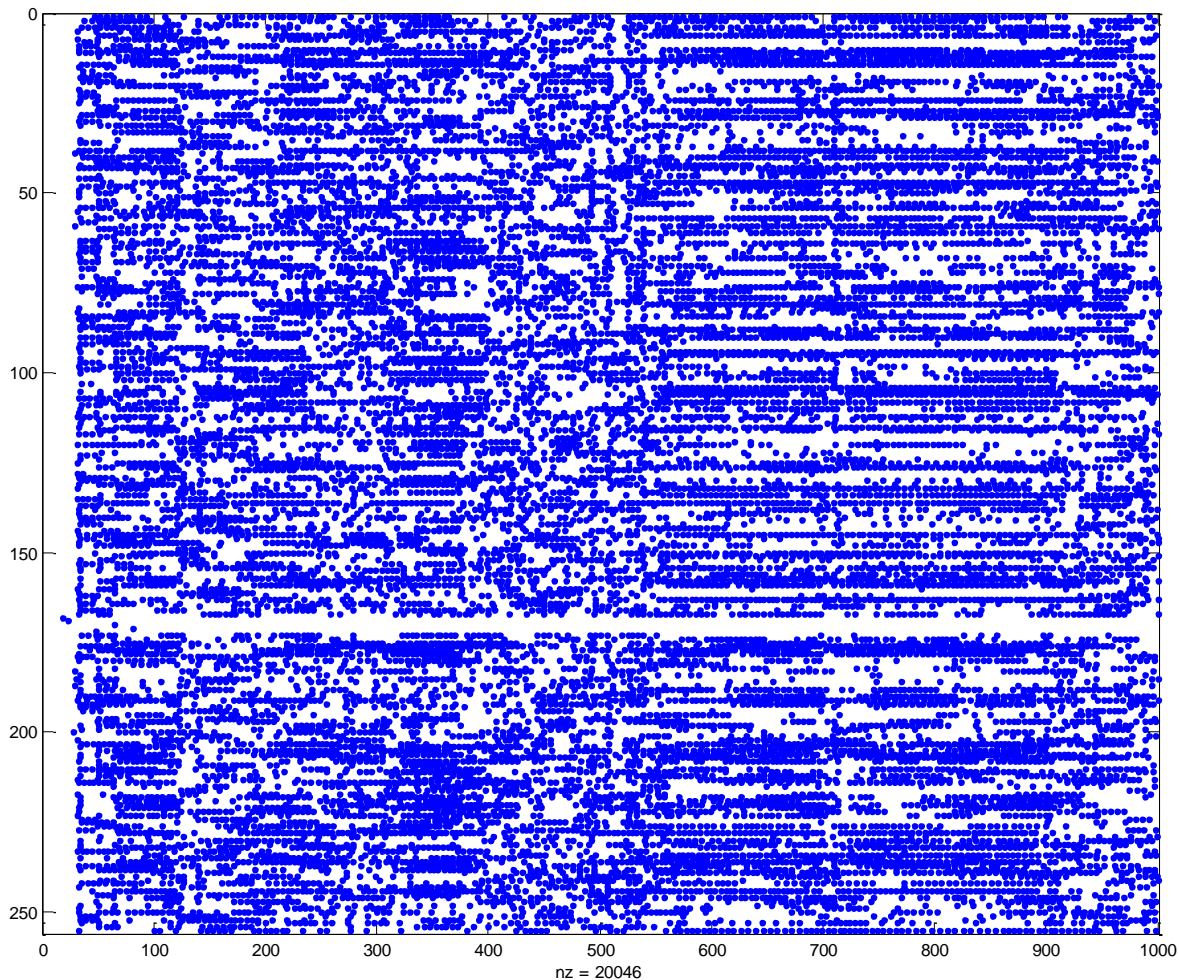
- excitatory (connection: Brette synapse)
 - Layers Connected
 - Bridge Equations
 - Connection Equations
- inhibitory (connection: Brette synapse)
 - Layers Connected
 - Bridge Equations
 - Connection Equations
- InputSynapses (connection: pExp2SynapseInB)
 - Layers Connected
 - Bridge Equations
 - Connection Equations

Connected to OrientDB: Local N2A DB Connected to PostgreSQL: Official N2A Database

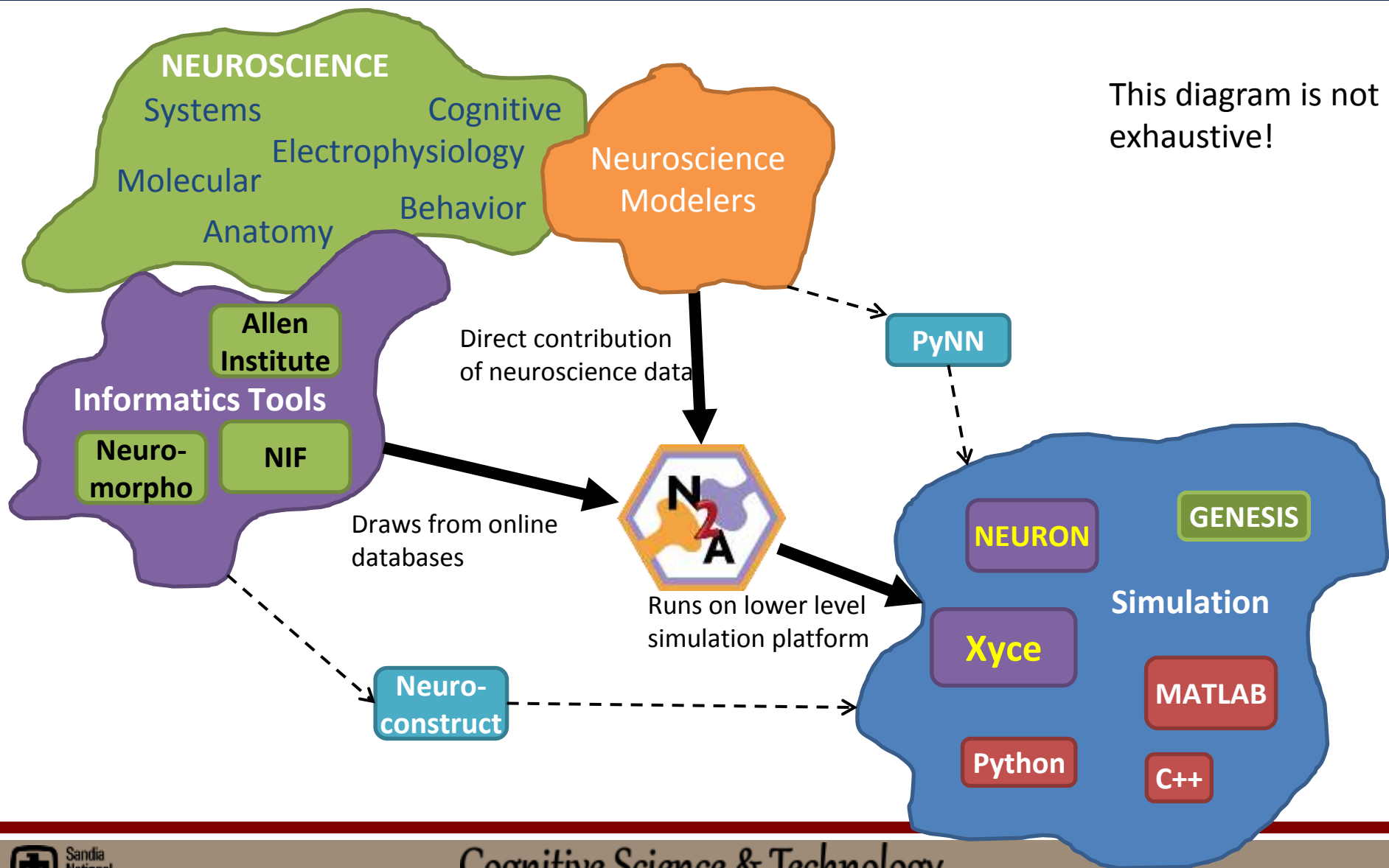
Recurrent model in N2A



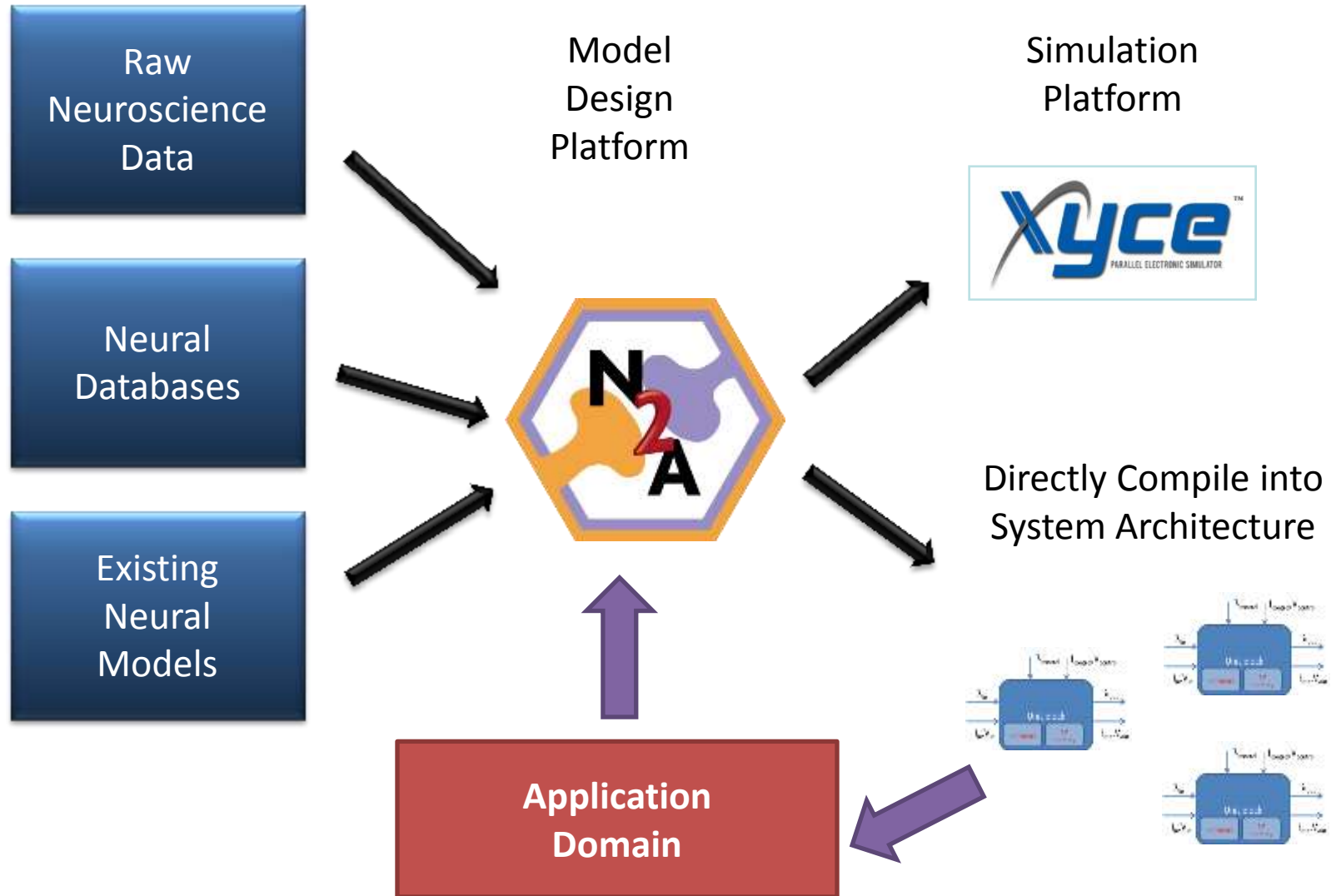
Recurrent model in N2A



Where Sandia Tools Fit Into Neuroscience



Direct application of tools to applications



Overview of Sandia Neuroscience

- Computational investigation of neural processes
- Novel tool development for community
- Mapping neural algorithms and insights into computing application

Sandia Comp Neuro Staff

- Michael Bernard
- Fred Rothganger
- Christy Warrender
- Richard Schiek
- Craig Vineyard
- Derek Trumbo
- Steve Verzi
- ...and more

